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Teknekron, Inc, Berkeley, Calif

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FUEL CYCLES FOR ELECTRICAL POWER GENERATION

Phase I

Towards Comprehensive Standards: The Electric Power Case

*Thomas H. Pigford**
Michael John Keaton
Bruce J. Mann

Prepared for the

Standards Research Branch
Implementation Research Division
Office of Research and Monitoring
Environmental Protection Agency

EPA No. 68-01-0561

By:

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The study presents an illustrative data base for estimating environmental effluents from alternative technologies for thermally generated electrical power. The data are to illustrate characteristics and possible magnitude of effluents to various environmental media and to illustrate the effect of choices of technology on the media effluents. The entire fuel cycle for each alternate technology is examined, representative sources of environmental effluents at each step in the fuel cycle are identified, and material and environmental quantities are indicated on a representative flow sheet for each of the following means of generating electric power: (1) Light-water nuclear reactor; (2) Low-sulfur bituminous coal; (3) Residual fuel oil; (4) Natural gas; (5) High-sulfur coal, with coal gassification and sulfur removal; (6) High-sulfur coal, with SO2 recovery by wet-limestone scrubbing; (7) Geothermal steam; (8) Breeder fission reactor; (9) Solar energy; (10) Thermonuclear fusion.

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Mr. Paul Gerhardt
Chief, Standards Research Branch
Implementation Research Division
Office of Research & Monitoring
Environmental Protection Agency
Room 1115, Xerox Building
1901 N. Ft. Myer Drive
Arlington, Virginia 22209

Dear Mr. Gerhardt:

We are pleased to submit the attached report, Fuel Cycles for Electric Power Generation. This document represents Teknekron's results for Phase I of the ongoing research program: "Towards Comprehensive Standards: The Electric Power Case".

The extensive data base developed in this study coupled with the Phase II analytical framework will provide a detailed methodology for evaluating alternative standard setting approaches (e.g., comprehensive multi-media standards, industry standards).

We look forward to continuing this research effort and we are confident that our results will be a major contribution to standards setting methodology.

Your guidance throughout this project and extensive coordination efforts with key EPA personnel are greatly appreciated.

Sincerely,

Michael John Keaton, Ph.D.
Project Director

MJK/brs

Att.

A Consortium of University Scientists and Engineers
Washington, D.C.
Berkeley, California
New York, New York

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I. INTRODUCTION

It is the purpose of this study to present an illustrative data base for estimating environmental effluents from alternative technologies for thermally generated electrical power. The data are to illustrate characteristics and possible magnitude of effluents to various environmental media and to illustrate the effect of choices of technology on the media effluents. The entire fuel cycle for each alternate technology is examined, representative sources of environmental effluents at each step in the fuel cycle are identified, and material and environmental quantities are indicated on a representative flow sheet for each of the following means of generating electric power:

1. Light-water nuclear reactor
2. Low-sulfur bituminous coal
3. Residual fuel oil
4. Natural gas
5. High-sulfur coal, with coal gassification and sulfur removal
6. High-sulfur coal, with SO_2 recovery by wet-limestone scrubbing
7. Geothermal steam
8. Breeder fission reactor
9. Solar energy
10. Thermonuclear fusion

The technologies include presently available means of electrical power generation and some examples of alternative means that may be available in the near future and distant future. To provide an illustrative but specific data base, within a study of limited scope and time, it was necessary to select examples from the very large number of alternative technologies, and from the very large number of permutations thereof, that are available now and projected for the future. For example, we have considered only one of the many kinds and resource locations of low-sulfur coal, only one of the many means of removing sulfur from high-sulfur coal prior to combustion, and only one of the many processes for removing SO_2 from combustion gases. Similarly, many developments which may be significant now or possibly in the future for low-effluent electrical power generation are not included, such as dual-cycle gas-turbine steam-turbine power generation from clean fuel gas, fuel cells, magnetohydrodynamic energy conversion, high temperature gas-cooled reactors, direct-conversion solar cells, and many others. Therefore, this study does not attempt to provide an encylopedic and definitive analysis of the environmental quantities of all possible fuel cycles, or even of a given fuel cycle. The flow sheets with specific material quantities illustrate the type of analysis that is an essential part of a meaningful cost-benefit assessment of alternate technologies for electrical power generation.

Of all the fuel cycles considered here, the greatest amount of specific and detailed data were available for the light-water nuclear plants. This is reflected by the relatively detailed analysis of the light-water nuclear plant fuel cycle given in this report. Consequently, the section on the light-water reactor fuel cycle illustrates the kind of technical data base and analyses which should be developed for all the fuel cycles before comparable environmental impact assessment can be made, and it also illustrates the additional data on material and environmental release quantities needed before a complete assessment of the environmental impact of this fuel cycle can be made.*

Each flow sheet is normalized to an assumed rate of electrical power generation of 1000 Mw(e) (10^9 watts). Material and environmental quantities are given in metric tonnes (Te), resulting from operating continuously for one year at full power, i.e., at 100% load factor. The quantities corresponding to actual operation at less than 100% load factor can be obtained by multiplying the flow sheet quantities by the appropriate fractional load factor.

No attempt has been made to assess environmental impacts resulting from the indicated effluents, although consideration of possible impact has influenced and, in some instances, restricted the choices of effluents to be shown.

Each fuel cycle flow sheet shows waste heat rejection by evaporative cooling. Alternative heat-rejection flow sheets for light-water nuclear plants and fossil-fueled plants are shown separately in Chapter 6. These, as well as the two flow sheets for reduction of SO_2 releases from high-sulfur coal (Chapters 7 and 8), are presented in a form so that the entire environmental effluents for a given combination of these technologies can be readily obtained by combining the flow sheets. For example, a light-water nuclear plant with dry-cooling heat rejection operates at lower thermal efficiency and requires more make-up fuel, as shown in Figure 6.7. The increased environmental effluents in all other portions of the light-water nuclear fuel cycle are then obtained by multiplying the quantities shown in the light-water fuel cycle flow sheet (Figure 2.1) by the ratio of fuel required for dry cooling to that shown on the flow sheet.

---

*Determination of environmental impact also requires data and analyses concerning the effects of releases. Environmental effects are not specifically considered in this report.

Brief consideration of electrical losses and land use associated with electrical power transmission is given in Chapter 13.

The overall fuel-cycle flow sheet format provides ready identification of the interaction of technology choices on effluents. The environmental choice of a particular power generation technology involves not only environmental considerations at the generating plant site but also throughout the entire fuel cycle. Choice of a particular waste-heat rejection system for a given power generating technology involves more than consideration of water-supply and thermal discharge. It affects the ability to discharge liquid effluents by dilution and dispersion, and it can result, in some instances, in increased effluents to the air.

To the extent possible, environmental release data from original sources have been examined for technical consistency, leading in many instances to corrections based on material balances and thermodynamic calculations. A few of the flow sheets include results of original calculations for this study. However, the flow sheets rely mainly upon data collected from various literature sources.

Selection of data and the limited data evaluation possible for this study reflect, in many instances, individual judgement by the authors. Therefore, the authors accept full and sole responsibility for the judgement implied herein and for errors of fact and interpretation which may be present.

2. ELECTRICAL POWER FROM URANIUM FUELED LIGHT-WATER REACTOR

2.1 Reactor Characteristics

The fuel cycle flowsheets for the light-water nuclear power plant, shown in Figure 2.1, is characteristic of the current generation of 1000 Mw(e) water reactors now operating or under construction. There are small differences in the fuel enrichment, i.e. the isotopic content of U^{235} in the fresh fuel, and in the overall thermal efficiencies of pressurized water reactors (PWR) and boiling water reactors (BWR). However, corrections for these small differences would result only in small perturbations in the quantities shown in the flowsheets. Where there are significant differences in environmental releases from these two types of water reactors, such as releases of radioactive tritium and radioactive gases at the power plant site, the characteristic releases for each of the two reactor types are indicated.

The fuel cycle characteristics are calculated on the basis of the equilibrium annual reload cycle whereby each fuel element operates for 1100 full-power days prior to discharge, corresponding to an average thermal exposure of 33,000 Mw days/Te U and an average thermal specific power of 30 Mw/Te U. The reactor core is refueled by a program of partial batch replacement, in which one third of the reactor core is replaced with new fuel each year. The make-up fuel is sintered uranium dioxide clad in zircaloy tubing, containing uranium enriched to 3.3% U^{235}.

The discharge fuel is stored at the reactor site for 150 days to

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

〰➤ ELECTRICAL ENERGY
- - - - ► AIRBORNE RELEASE
⇨ LIQUID EFFLUENT
➡ SOLID EFFLUENT

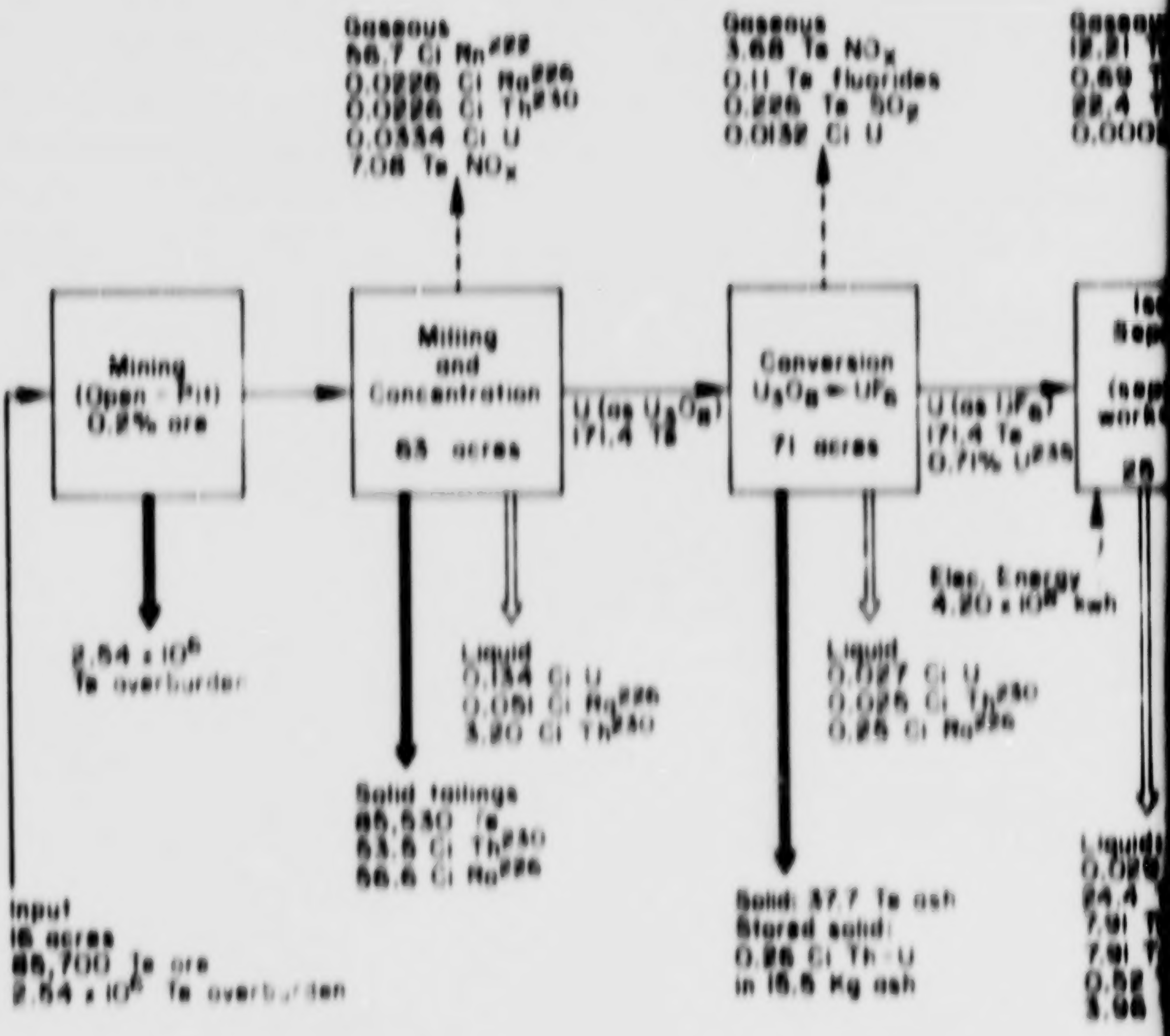
Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

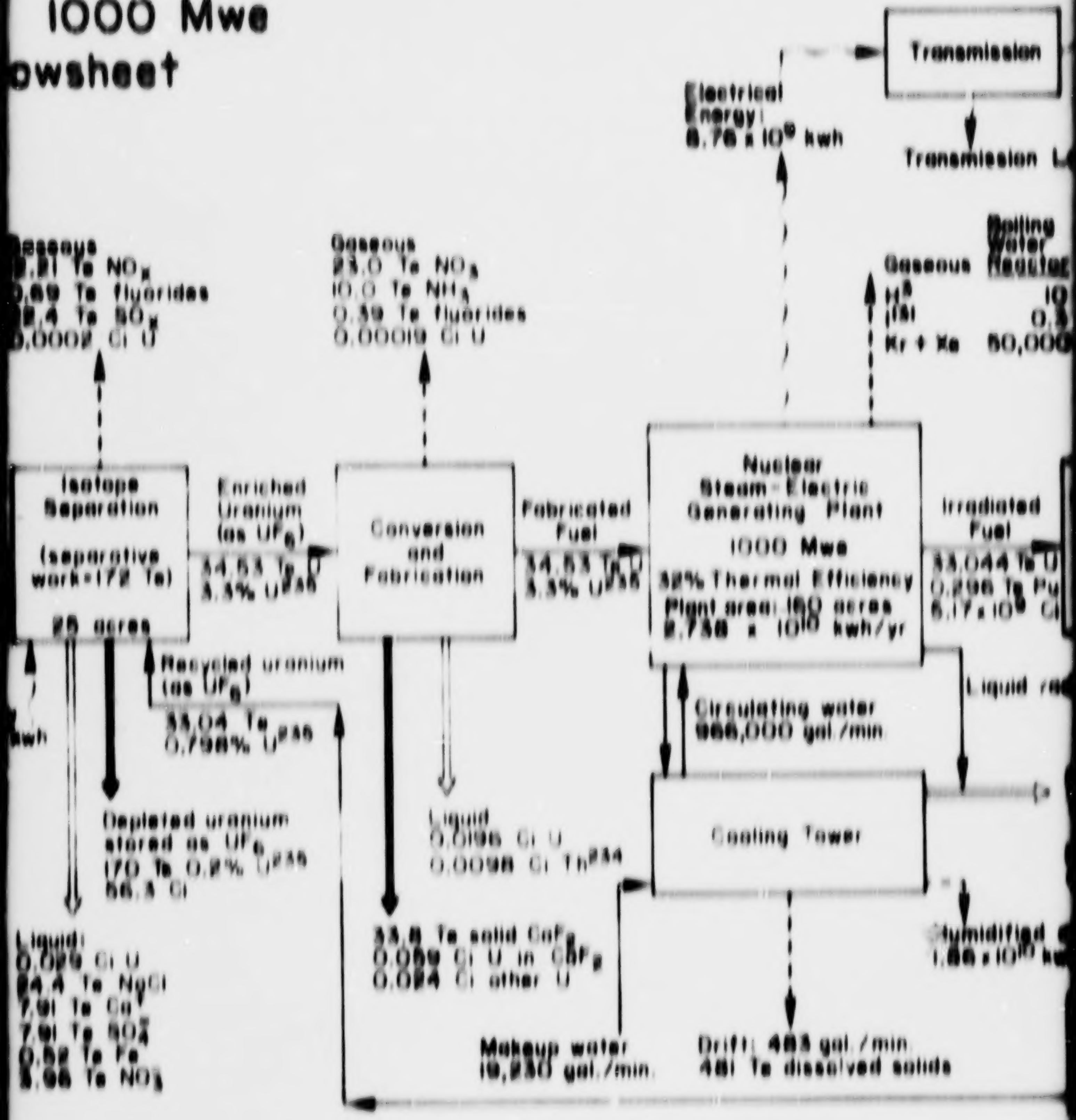
TEKNEKRON, INC.
BERKELEY, CALIFORNIA

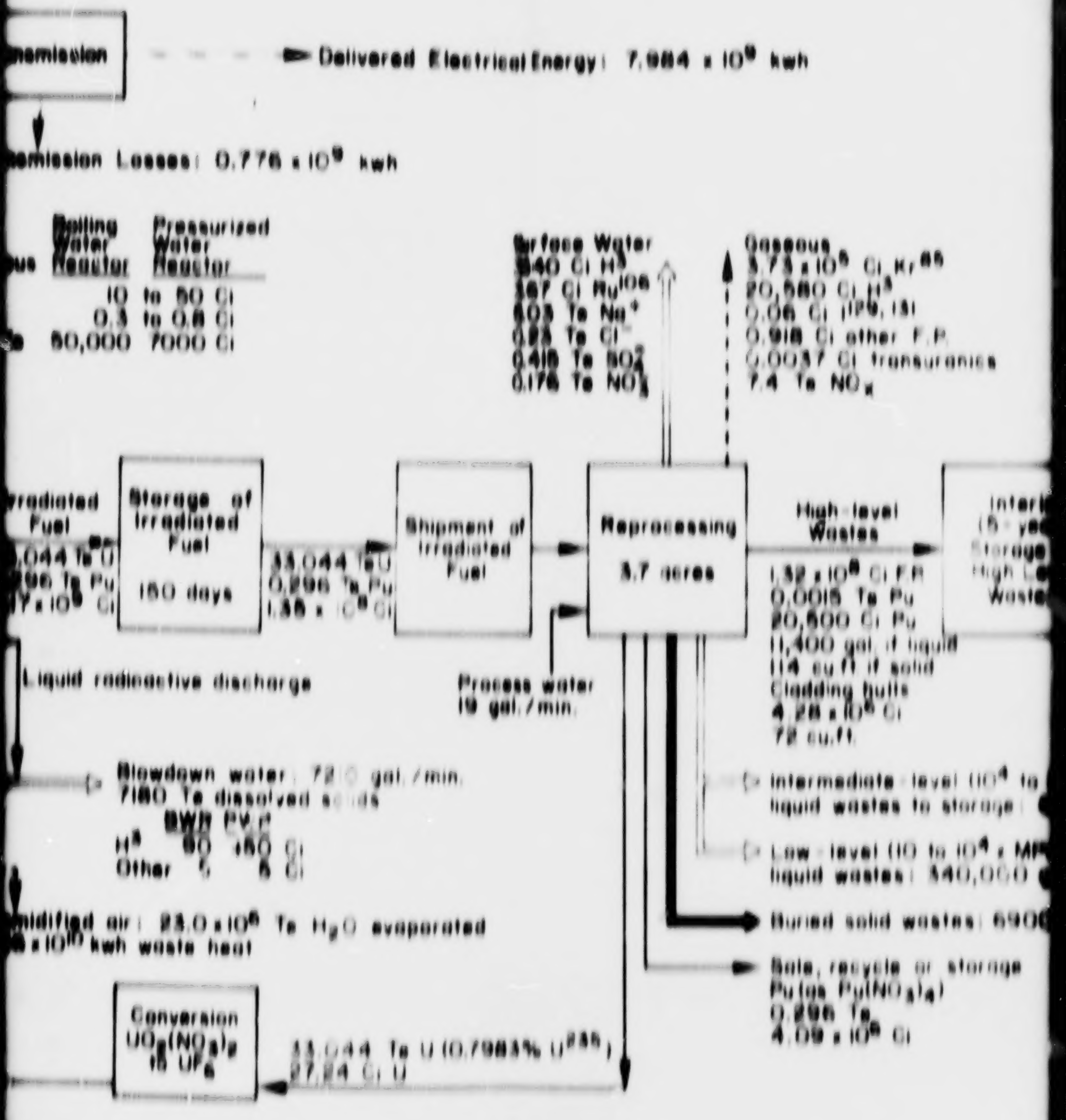
Figure 2.1

Light Water Reactor Nuclear Power Plant IO
Material And Environmental Release Flows

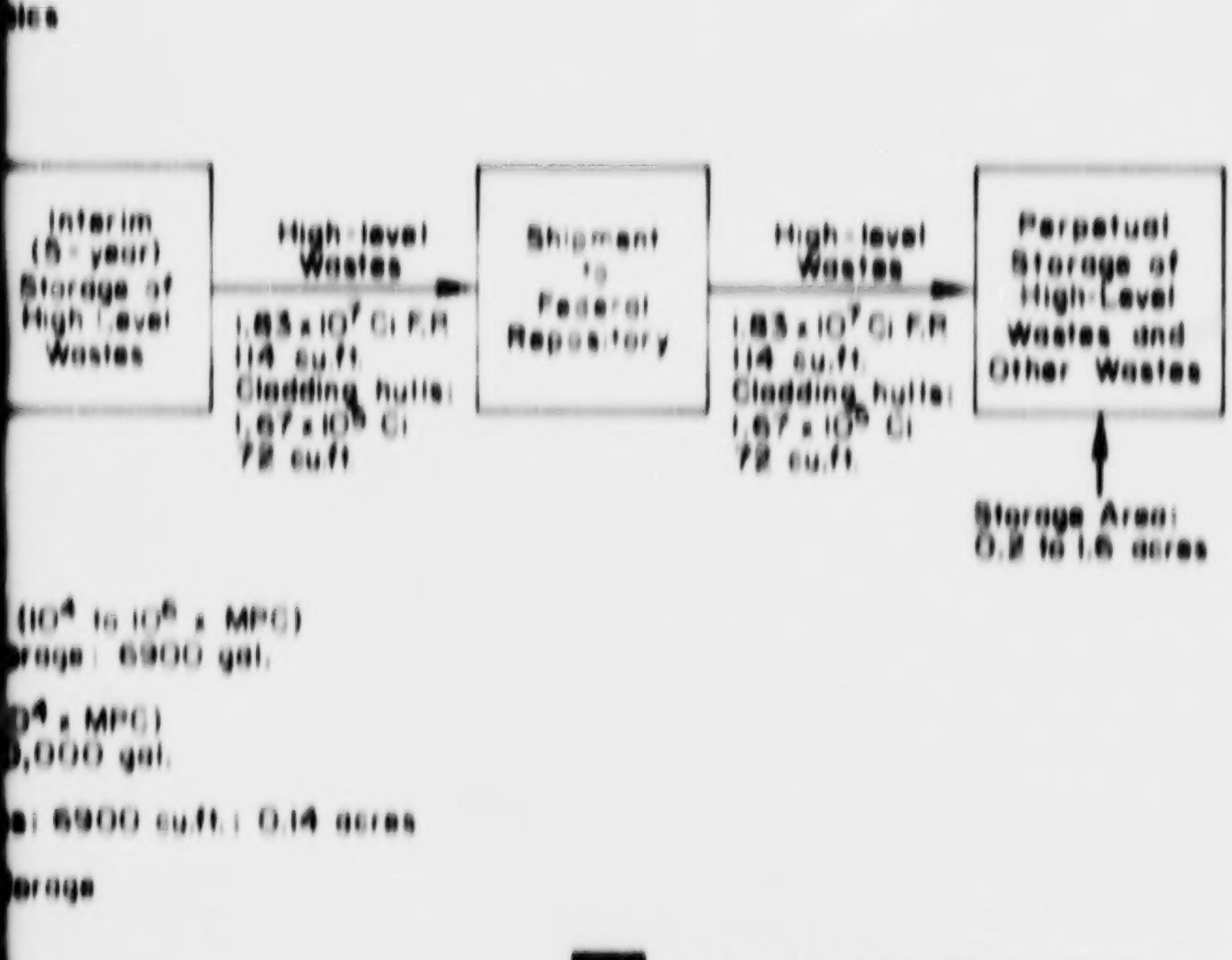

Gaseous
56.7 Ci Rn^{222}
0.0226 Ci Ra^{226}
0.0226 Ci Th^{230}
0.0554 Ci U
7.08 Te NO_x
Gaseous
3.68 Te NO_x
0.11 Te fluorides
0.226 Te SO_2
0.0132 Ci U
Gaseou
12.21 T
0.69 T
22.4 T
0.000
Mining
(Open - Pit)
0.2% ore
Milling
and
Concentration
65 acres
U (as U_3O_8)
171.4 Te
Conversion
$U_3O_8 \rightarrow UF_6$
71 acres
U (as UF_6)
171.4 Te
0.71% U^{235}
Is
Sep
(sep
work
25
Elec. Energy
4.20×10^8 kwh
2.54×10^6
Te overburden
Liquid
0.154 Ci U
0.051 Ci Ra^{226}
3.20 Ci Th^{230}
Liquid
0.027 Ci U
0.026 Ci Th^{230}
0.25 Ci Ra^{226}
Solid tailings
85,530 Te
53.5 Ci Th^{230}
56.6 Ci Ra^{226}
Input
16 acres
85,700 Te ore
2.54×10^6 Te overburden
Solid: 37.7 Te ash
Stored solid:
0.26 Ci Th - U
in 15.5 Kg ash
Liquid
0.029
24.4
7.91 T
7.91 T
0.52
3.96

1000 Mwe
owsheet


Transmission
Electrical Energy: 8.76 x 10^9 kwh
Transmission L
Boiling Water Reacto
Gaseous
H3 10
I131 0.3
Kr + Xe 50,000
aseous
0.21 Te NOx
0.69 Te fluorides
22.4 Te SOx
0.0002 Ci U
Gaseous
23.0 Te NOx
10.0 Te NH3
0.39 Te fluorides
0.00019 Ci U
Isotope Separation
(separative work=172 Te)
25 acres
Enriched Uranium (as UF6)
34.53 Te U
3.3% U235
Conversion and Fabrication
Fabricated Fuel
34.53 Te U
3.3% U235
Nuclear Steam-Electric Generating Plant
1000 Mwe
32% Thermal Efficiency
Plant area: 160 acres
2.758 x 10^10 kwh/yr
Irradiated Fuel
33.044 Te U
0.296 Te Pu
6.17 x 10^9 Ci
Recycled uranium (as UF6)
33.04 Te
0.798% U235
wh
Circulating water 966,000 gal./min
Liquid ra
Depleted uranium stored as UF6
170 Te 0.2% U235
56.3 Ci
Liquid
0.0196 Ci U
0.0098 Ci Th234
Cooling Tower
Humidified a
1.86 x 10^10 k
Liquid:
0.026 Ci U
24.4 Te NaCl
7.91 Te Ca
7.91 Te SO4
0.52 Te Fe
3.96 Te NO3
33.8 Te solid CaF2
0.059 Ci U in CaF2
0.024 Ci other U
Makeup water 19,230 gal./min.
Drift: 483 gal./min.
481 Te dissolved solids



nsmission
Delivered Electrical Energy: 7.984 x 10⁹ kwh
nsmission Losses: 0.776 x 10⁹ kwh
Boiling Water Reactor
Pressurized Water Reactor
ous
10 to 50 Ci
0.3 to 0.8 Ci
te 50,000 7000 Ci
Surface Water
540 Ci H³
367 Ci Ru¹⁰⁶
603 Te Na⁺
0.85 Te Cl⁻
0.416 Te SO₄
0.176 Te NO₃
Gaseous
3.75 x 10⁵ Ci Kr⁸⁵
20,580 Ci H³
0.06 Ci I¹²⁹,¹³¹
0.916 Ci other F.P.
0.0037 Ci transuranics
7.4 Te NOₓ
rradiated Fuel
.044 Te U
296 Te Pu
7 x 10⁸ Ci
Storage of Irradiated Fuel
150 days
33.044 Te U
0.296 Te Pu
1.35 x 10⁸ Ci
Shipment of Irradiated Fuel
Reprocessing
3.7 acres
High-level Wastes
1.32 x 10⁸ Ci F.P.
0.0015 Te Pu
20,500 Ci Pu
11,400 gal. if liquid
114 cu.ft. if solid
Cladding hulls
4.28 x 10⁶ Ci
72 cu.ft.
Interi
(5-ye
Storage
High Le
Waste
Liquid radioactive discharge
Process water
19 gal./min.
Blowdown water: 7210 gal./min.
7160 Te dissolved solids
BWR PWR
H³ 60 450 Ci
Other 5 6 Ci
Intermediate-level (10⁴ to
liquid wastes to storage:
Low-level (10 to 10⁴ x MP
liquid wastes: 540,000
Buried solid wastes: 690
midified air: 23.0 x 10⁶ Te H₂O evaporated
x 10¹⁰ kwh waste heat
Sale, recycle or storage
Pu as Pu(NO₃)₄
0.296 Te
4.09 x 10⁵ Ci
Conversion UO₂(NO₃)₂ to UF₆
33.044 Te U (0.7983% U²³⁵)
27.24 Ci U


ples
Interim
(5-year)
Storage of
High Level
Wastes
High-level
Wastes
1.83 x 10^7 Ci F.P.
114 cu.ft.
Cladding hulls:
1.67 x 10^5 Ci
72 cu.ft.
Shipment
to
Federal
Repository
High-level
Wastes
1.83 x 10^7 Ci F.P.
114 cu.ft.
Cladding hulls:
1.67 x 10^5 Ci
72 cu.ft.
Perpetual
Storage of
High-Level
Wastes and
Other Wastes
Storage Area:
0.2 to 1.6 acres
(10^4 to 10^6 x MPC)
orage: 6900 gal.
0^4 x MPC)
0,000 gal.
s: 6900 cu.ft.: 0.14 acres
orage

TEKNEKRON, INC.

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

allow time for decay of radioiodine and U^{237}. The discharge fuel is then shipped to a reprocessing facility where the fuel is separated into uranium, plutonium, and mixed fission products. The recovered uranium, containing about 0.8% U^{235}, is returned as an input to the isotope-separation plant for re-enrichment. The quantities of trans-uranic and fission-product nuclides in the irradiated fuel at discharge and at various cooling times after discharge were calculated using the Phoebe code(1,2). For the purpose of the present study it is assumed that the 0.200 tonnes of plutonium recovered yearly from the discharge fuel is stored.

The issue of plutonium utilization and its relevance to the analysis of material quantities and environmental impact of light-water nuclear power plants now being constructed is discussed in Section 2.12.

2.2 Mining

Uranium is assumed to be obtained from carnotite ore, nominally containing 2% uranium(3). Open-pit mining is assumed(4), with a yield of 5400 Te ore(5) and 180,000 Te overburden(6) per acre of land disturbed. Mine drainage water discharged to the ground is calculated on the basis of 1000 gal/yr per Te of ore extracted(7). The yearly quantity of 171.4 Te of uranium to be contained in the ore is based upon the yearly make-up to the reactor of 34.53 Te and a material balance on the isotope separation plant with the indicated enrichments in the feed, the tails, the product, and the recycle uranium. No losses of uranium in the processing operations were considered in calculating this material balance.

2.3 Milling and Concentration

A model milling plant with a capacity of 900 Te per year of U_3O_8 is estimated to occupy 300 acres(8). This scales to 63 acres attributable to the milling of 171.4 Te of uranium per year for the light-water reactor flowsheet. The process water requirement is 0.42 million gallons per Te of uranium processed(8). Waste liquors from milling are estimated at 1800 Te per Te of uranium processed(8), containing the following concentrations of radionuclides(8,10).

uranium	5×10^{-7} µc/ml
Ra^{226}	1.9×10^{-7} µc/ml
Th^{230}	1.2×10^{-5} µc/ml

These concentrations multiplied by the yearly volume of liquid effluent result in the yearly quantities of radionuclides shown in the flowsheet. The waste liquor is stored in a retention basin to prevent discharge into the surface water and to minimize percolation into the ground.

Airborne radionuclide releases from the milling process include gaseous radon-222, a radioactive decay daughter in the U^{238} decay chain, and particulates of uranium and the uranium-decay daughters. Natural uranium contains 99.28% U^{238}, with a half life of 4.51 billion years, corresponding to 0.3308 curies of U^{238} per tonne of uranium. Even though the half life of U^{235} is only 0.71 billion years, its relatively small concentration results in only 0.01513 curies of U^{235} per tonne of natural uranium. Therefore, the radioactivity in the milling wastes will be dominated by the U^{238} decay daughters. The yearly throughput of 171.4 Te of uranium corresponds to 56.7 curies of U^{238}, accompanied by an equal number of curies of each of the U^{238} decay daughters which are formed without chain branching. Therefore the total amount of Rn^{222} is 56.7 curies. It is assumed that all radon is released as gaseous effluent. The estimates of the releases of airborne particulates of Ra^{226}, Th^{230}, and uranium are based on data in references (6) and (10).

The greatest amount of radioactivity separated from natural uranium in milling appears in the solid tailings. Here it is assumed that all the radioactive daughters originally present in the uranium ore and not accounted for in the gaseous and liquid releases appear in the tailings. The most important species to be considered is 1622-year Ra^{226}, which is indicated on the flowsheet. The possible leaching of the chemical compounds containing Ra^{226} into the ground waters and surface waters near the milling storage site is an important environmental consideration.

Annual land use for solid tailings storage is estimated(5) on the basis of 1.9 acres per 100 tonne of uranium processed.

2.4 Conversion of U_3O_8 to UF_6

The conversion operations involve removal of chemical contaminants and impurities from the uranium and conversion to the volatile hexafluoride as feed to the isotope separation plant. Conversion to the hexafluoride involves reduction to UO_2, hydrofluorination to UF_4 with anhydrous hydrogen fluoride, and fluorination to UF_6 with gaseous fluorine. In the hydrofluor process purification is then accomplished by fractional distillation of the UF_6. The principal environmental releases from this process are gases and solids. In the alternative solvent-extraction purification process, the U_3O_8 is first converted to uranyl nitrate in aqueous solution, which is then contacted with an immiscible organic liquid phase containing a complexing agent to extract the uranium preferentially from the impurities. The purified uranium is then converted to UF_6. Purification by solvent extraction involves larger quantities of liquid wastes but smaller quantities of gaseous and solid wastes than the hydrofluor process. Both processes are used industrially, and the flowsheet quantities in this study are based upon a model plant analyzed by the AEC, in which each of the two processes contributes to half the production capacity. The environmental quantities for the AEC model plant, translated to amounts per ton of uranium processed, are tabulated in Table 2.1.

Table 5.1

Environmental Quantities for U_3O_8 - UF_6 Conversion*

Natural Resource Use(10)	
Land, acres per 1 Te U/yr production capacity	
Temporarily committed	1.88
Undisturbed area	1.76
Disturbed area	0.11
Permanently committed	0.011
Water, gal/Te U	
Discharged to air	6.06×10^4
Discharged to surface water	56.4×10^4
Fossil Fuel	
Electrical energy, kwh/Te U	1.18×10^3
Natural gas, cu.ft./Te U	1.7×10^6
Effluents(10)	
Chemicals, Te/Te U	
Combustion gases	
SO_x	0.16
NO_x	0.056
hydrocarbons	0.0035
CO	0.0011
Other gases	
F	0.0008
Solids	0.22
Radiological, Ci/Te U	
Gases	
uranium	0.00007
Liquids	
Ra226	0.000140
Th230	0.00140
uranium	0.000146
Solids	
Other than high-level	0.00104
Thermal, kwh/Te U	4,880

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*Environmental release quantities shown on the flowsheet are obtained by multiplying the above data by the uranium throughput.

2.6 Uranium Enrichment

The feed streams to the isotopic separation plant consist of natural hexafluoride, containing 0.711% U^{235} in uranium, and uranium recycled from fuel reprocessing. In this flowsheet the recycled uranium is calculated to contain 0.7903% of U^{235}. Material balances on total uranium and on the contained U^{235} yield the uranium quantities shown on the flowsheet.

The total annual separative work to perform the indicated isotopic separation is obtained by summing the products of the uranium output quantities and the separative potential functions and subtracting the similar products involving the uranium input quantities(3). The electrical input to the gaseous diffusion plant to perform this isotopic separation is calculated from data in reference (12), using a ratio of 2425 kwh of electrical energy per tonne of separative work (SW), for a plant of total plant capacity of 8750 Te SW per year. The resulting annual electrical requirement of 4.20 x 10^8 kwh represents over 98% of the total energy input for the entire fuel cycle(4). It represents 4.8% of the net electrical output from the 1000 Mw(e) nuclear power plant. For a net thermal efficiency of 32% for the light-water nuclear power plant itself, the electrical consumption for isotopic separation reduces the overall fuel cycle thermal efficiency to 30.5%. Essentially all of the electrical energy input to isotope separation appears eventually as waste heat, to be dissipated to a surface water coolant or as humidified air from an evaporative cooling tower.

Additional environmental releases are scaled according to separative work, using the above data in electrical energy input and data from an AEC summary of the total environmental releases for the present diffusion-plant complex with a total capacity of 10,000 Te/yr of separative work[4]. The 172 Te/yr of separative work required for the light-water nuclear power plant amounts to 1.04% of the capacity of the total complex. The environmental release, expressed as quantities per unit of separative work (SW), are listed in Table 2.2. Effluents arising directly from the generation of electrical power to operate the diffusion plant are not shown.

Table 3.5

Environmental Quantities for Uranium Enrichment

Natural Resource Use	
Land(4), acres per Te SW/yr	
Temporarily committed	0.017
Undisturbed area	0.008
Disturbed area	0.009
Water(4), gal/Te SW	
Discharged to air (diffusion plant cooling)	7.1 x 10^6
Discharged to surface water at electrical generating plant	8.6 x 10^7
Electrical energy(10), kwh/Te SW	2435 (mine)
Effluents(4)	
Chemical, lb/Te SW	
Gases from coal-fired electrical power generation	
SO_x	24
NO_x	6.4
Hydrocarbons	0.06
CO	0.15
Particulates	6.6
Gases from chemical processing	
SO_x	0.12
NO_x	0.021
Fluorides	0.004
Liquids	
Ca^{++}	0.040
Cl^-	0.021
Na^+	0.021
SO_4	0.044
Fe	0.003
NO_3	0.035
Radiological, Ci/Te SW	
Gases	
uranium	0.000017
Liquids	
uranium	0.00017
Thermal, kwh/Te SW	
at diffusion plant	2435
at electrical generating plant (38% thermal efficiency)	3972
total	6407

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*Environmental release quantities shown on the flowsheet are obtained from the above data, scaling according to the total separative work.

2.6 Fuel Conversion and Fabrication

The slightly enriched uranium hexafluoride shipped from the isotope-separation facility is hydrolysed to uranyl fluoride, converted to ammonium diuranate, and calcined to the dioxide. The dioxide powder is pelletized, sintered, and loaded into stainless or zircalloy tubing which is then capped and welded. The fuel rods, each about 12 feet long and slightly less than 1/2 in. in diameter, are assembled in arrays to be handled as fuel elements.

Scrap material from fuel fabrication is dissolved in nitric acid, purified by solvent extraction, calcined and reduced to the dioxide.

The most significant chemical effluents are fluorine, fluorine compounds, and nitrogen compounds. The bulk of the fluorine released from the UF_6 appears ultimately as solid CaF_2 resulting from lime neutralization. The environmental effluents from a representative model fuel fabrication plant, with a capacity of 3 Te U/day, have been defined by the AEC(4). These data, translated to environmental quantities per tonne of uranium fabricated, are listed in Table 2.5.

Table 5.3

Environmental Quantities for Fuel Conversion and Fabrication*

Natural Resource Use[4]	
Land, acres per Te U/yr	
Temporarily committed	0.0027
Undisturbed area	0.0016
Disturbed area	0.0011
Permanently committed	0
Water, gal/Te U	1.40×10^6
Electrical energy, kwh/Te U	4.00×10^4
Natural gas, cu.ft./Te U	1.00×10^5
Effluents[4]	
Chemical, Te/Te U	
Gases from coal-fired electrical power generation	
SO_x	0.66
NO_x	0.17
Hydrocarbons	0.002
CO	0.004
Process gases	
F^-	0.00014
Liquids	
N as NH_3	0.06
N as NO_3	0.16
F^-	0.011
Solids (calculated as stoichiometrically equivalent to UF_6 feed)	
CaF_2	0.90
Radiological, Ci/Te U	
Gases	
uranium	0.000006
Liquids	
uranium	0.0006
Solids (buried)	
uranium	0.0017
Thermal, kwh/Te U	7.0×10^4

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*Environmental release quantities shown on the flowsheet are obtained by multiplying the above data by the uranium throughput.

2.7 Nuclear Power Plant Operation

Environmental releases of concern at nuclear power stations are radiological, chemical, and thermal. The nature of the thermal releases and the alternative technologies to control these releases are discussed in the section on waste-heat rejection systems. The chemical releases are those characteristic of water treatment systems for steam power plant operation and are shown in the heat-rejection flowsheets. The radiological releases considered in these flowsheets are those resulting from normal operation.

The rate of formation and inventory of the radionuclides important in considering environmental radiological releases are shown in Table 2.4, calculated for a typical 1000 MW(e) light-water reactor by means of the Phoebe code(1,2). The radionuclide inventories are calculated on the basis of all fuel elements in the reactor being at the discharge composition. This is a good assumption for those radionuclides whose half lifes are short compared with the fuel exposure life of three years. For longer half life radionuclides, the actual inventory in the reactor will be less than the amount listed, depending upon the fuel management program. For example, for a partial batch replacement of one third of the core every year, the inventory of 12.33-year tritium will be about two thirds of the inventory listed in the table. The yearly quantities in the discharge fuel are essentially independent of the fuel management program.

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
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[illegible]		[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]							
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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In addition to the radioactive tritium resulting from fission, as listed in Table 2.4, tritium is also produced by fast-neutron reactions in boron used for reactor control, as well as by neutron reactions in lithium contaminants. This tritium probably remains in the matrix of the solid, metal-clad boron control absorbers. Also, the absence of a phase change in the primary coolant of pressurized water reactors makes it possible to use soluble boron dissolved in the coolant, for reactivity control. Tritium produced from this dissolved boron contributes to the increased tritium environmental releases from pressurized water reactors.

The fission-product radioactivity involved in environmental releases in normal operation first reaches the reactor coolant through defects in cladding, except for tritium which also reaches the coolant by diffusing through the cladding. The principal fission products which reach the coolant in this way are radioiodine and the noble gases, krypton and xenon, which diffuse from the fuel matrix. Smaller quantities of non-volatile fission products recoil from the fuel matrix and escape through defective cladding. Fission products are also formed on the outer surface of the cladding due to uranium contaminants. Additional radionuclides formed in the coolant include activated corrosion products, tritium formed due to neutron reactions with dissolved boron and lithium, N^{16} formed by (n,p) reactions with oxygen, 9.96-min. N^{13} formed by (p,α) reactions with oxygen and (α,n) reactions with B^{10}, and 110-min. F^{18} formed by (p,n) reactions with oxygen.

The primary source of gaseous radioactive effluents arises from the extraction of non-condensable gases from the primary circuit. Secondary sources of gaseous effluents are gases evolved from primary coolant leaking from the reactor circuit, gases evolved from primary coolant handled in low-pressure coolant purification operations, gases evolved from primary coolant during refueling operations, gases evolved from the PWR steam (secondary) system containing radionuclides leaked from the primary system, gases evolved in the air-sparging of process equipment such as ion-exchange resin storage tanks, and gases evolved in the liquid waste handling system. Radionuclides released as gaseous effluents are krypton, iodine, tritium, and particulates, and tritium as tritiated water vapor.

Radioactive Noble Gases

In a pressurized water reactor power plant the primary gaseous source is of relatively small volume, because there is no pressure gradient for leakage of noncondensable gases into the primary coolant system and because the volume of noncondensable hydrogen and oxygen from radiolytic decomposition is suppressed by hydrogen pressurization. The noncondensable gas from primary sources is held up for 30 days, sufficient for all the noble-gas radionuclides other than 10.76-yr. Kr^{85} to be reduced to negligible levels by radioactive decay. It then flows through particulate filters and a charcoal filter for iodine removal and discharges to the atmosphere at the roof vent. Typically, the released krypton dilutes rapidly to a concentration far below the allowable level by the time it reaches the site boundary.

Radioactive noble gas effluents are of greater magnitude in boiling water reactors because of the much higher volume of noncondensables to be extracted from the reactor coolant system. Without the benefits of hydrogen pressurization of the PWR, the BWR generates about 180 cu.ft./min of hydrogen and oxygen by radiolytic decomposition. Also, because the reactor coolant is the working fluid and expands in the turbine to pressures below atmospheric, about 10 to 40 cu.ft./min of air leaks into the primary coolant and interferes with condensation. The air and other noncondensables must be continuously removed by a steam ejector. A gas holdup tank to provide significant radioactive decay time would be exorbitantly large. The practice in many large boiling water reactors already licensed and operating is to hold the gas up for 30 minutes, pass it through a particulate filter, and discharge it from a tall stack to enhance atmospheric dilution. The released gas thus contains a relatively high activity of the short-lived krypton and xenon radionuclides. The yearly release rate is typically about 3 million Ci/yr.

Newer BWR power plant installations employ additional technology to reduce noble-gas radioactive emissions. The air ejector gas passes through a recombiner to remove the explosion hazard from the hydrogen and oxygen formed by radiolytic decomposition of reactor water. The gas then passes through a charcoal bed where the continued absorption, diffusion, and desorption of krypton and xenon provide an effective delay time of about 10 to 24 hours for krypton and 10 to 15 days for xenon(13). The gas is then filtered and released at the roof vent. Boiling water reactor plants employing this technique for reducing noble-gas radionuclide effluents are expected to have noble-gas releases in the neighborhood of 30,000 to 50,000 Ci/yr(13,14).

If further reduction in the release of noble-gas radionuclides were desirable and justified, the small volume of gas evolved as the primary gaseous effluent in pressurized water reactors could be stored in compressed-gas tanks. Krypton and xenon can be removed from the steam-ejector gas in boiling water plants by cryogenic adsorption or condensation or by absorption in a chilled organic.

Gaseous Radioiodine

The secondary sources can, however, account for significant quantities of radioactive iodine in the gaseous effluents. Because iodine is selectively taken up by the thyroid gland when ingested, and because it can be transported to the more critical infant recipients via the milk-food chain, a small number of curies of radioiodine can be far more significant biologically than the relatively large releases of noble-gas radionuclides. For a more specific comparison, the maximum permissible concentrations of Kr^{85} and I^{131} in the present 10 CFR 20 regulations(15) and the design-objective concentrations proposed in 10 CFR 50, Appendix I(16), are listed below. Also listed are the yearly release rates which would result in a yearly average concentration complying with the quoted regulation, calculated on the basis of a typical site-boundary dilution factor of 2×10^{-12} sec/ml for building-vent release(17).

Table 2.5

Allowable Concentrations and Yearly Releases of Kr^{85} and I^{131} for Assumed Atmospheric Dilution

	Kr^{85}	I^{131}
maximum permissible concentration for unrestricted exposure of 500 mrem/yr, 10 CFR 20, microcuries per milliliter	3×10^{-7}	1×10^{-10}(a)
calculated(b) allowable yearly release, curies/yr	4.73×10^{6}	1580(a)
design-objective concentrations, proposed Appendix I, 10 CFR 50, microcuries per milliliter	6×10^{-8}(c)	1×10^{-15}
calculated(b) allowable yearly release, curies/yr	9.5×10^{5}	0.0158

(a) When allowance is made for the milk food chain the allowable iodine concentration and yearly release is lower by a factor of 700.

(b) Calculated by dividing the allowable specified concentration by the assumed yearly average dilution factor of 2×10^{-12} sec/ml for releases from top of reactor building. The dilution factor is the concentration at the site boundary divided by the emission rate at the reactor.

(c) Calculated from the dose specification of 10 mrem/yr in Appendix I.

The primary noncondensable gas streams in PWR and BWR plants are passed through charcoal, which is expected to remove about 99% of the contained iodine(17)*. In the BWR plants, radioiodine is associated with the secondary gaseous effluents, such as the steam leaking through the turbine gland seal, direct leakages of reactor coolant into the reactor and turbine building, liquid radiological waste system vents, and air sparging of process equipment for handling ion exchange resins(17).

The secondary sources are expected to contribute a greater source of gaseous iodine release for pressurized water reactors, even though only minor quantities of iodine are discharged via the primary gas treatment system(17). Reactor coolant water containing dissolved radioiodine leaks into the steam system, and a portion of this iodine is evolved with noncondensables through the steam ejector system. An even larger source of gaseous radioiodine appears in the ventilation system for the auxiliary building where the reactor coolant is processed. Another source of gaseous radioiodine effluent results from the monthly purge of air within the reactor contaminant building(17).

The reported yearly releases of gaseous radioiodine from existing BWR and PWR power plants for the year 1971 have been published by the AEC(18), and are summarized in Table 2.6.

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*The efficiency for removing iodine by charcoal depends upon the moisture content and upon the fraction of the iodine in the form of methyl iodine. Methyl iodide does not absorb readily on charcoal.

Table 2.6

Radioactive Releases for 1000 MW(e) Plant

Extrapolated from 1977 Reported Releases

	thermal power[b] MW(t)	thermal energy produced[a] MW-days	reported radioactive releases[a] Ci/facility	radioactive releases extrapolated to 1.00 x 10⁶ MW-days thermal energy[b] Ci/facility
BWR	700	91,200	3.40	5.60
	to	to	to	to
	2 x 2527	513,000	8.73	18.0
PWR	400	200,000	< 0.0003	0.0007
	to	to	to	to
	2600	377,000	0.77	1.60

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[a] NRC, Report on Releases of Radioactivity in Effluents from Nuclear Power Plants for 1977, Directorate of Regulatory Operations, December, 1978.

[b] Corresponding to 1000 MW(e), 33% thermal efficiency, 80% load factor, one-year operation.

Releases of radioiodine from BWR plants of thermal capacity varying from 700 Mw(e) to 2527 Mw(e) varied from about 0.6 to 4 Ci. Normalizing these data according to the reported thermal energy produced by each of these reactors during the year 1971 and scaling to the energy produced by a 1000 Mw(e) nuclear power plant operating at 33% thermal efficiency for a year at 100% load factor, releases varying from 0.28 to 10 Ci/yr of gaseous radioiodine are predicted. Similarly reported data for PWR plants with capacities from 600 Mw(e) to 2000 Mw(e), scaled to the 1000 Mw(e) plant at 100% load factor, are in the range of 0.0001 to 1.6 Ci of radioiodine. These reported releases are based upon primary sources of effluents. It is difficult to monitor radioiodine in the concentrations of significance in many of the secondary sources and reported operating experience does not yet verify the iodine releases associated with these sources.

For the purpose of the present flowsheet the gaseous radioiodine releases are based upon estimates for modern light-water power reactors with augments for control of radioiodine from the primary sources. The radioiodine releases shown are 0.32 Ci/yr for the BWR(14) and 0.8 Ci/yr for the PWR(17).

Tritium in Gaseous Effluents

Tritium appears in the gaseous releases as tritiated water vapor carried in the air streams. The releases here are based upon Rodger's(17) estimates of 100 Ci/yr of tritium released to the BWR coolant, and 600 Ci/yr to the PWR reactor coolant and his estimate that 10% of the tritium released to the coolant will appear in the gaseous releases as tritiated water vapor, the remaining 90% appearing in the liquid effluents. If additional technology were employed to decrease tritium in the liquid effluents, some increase in the release of gaseous tritium would be expected.

Radioactive Particulates in Gaseous Effluents

The AEC report of radioactive effluent releases for 1971 lists airborne radioactive particulate releases for BWR and PWR plants(10). Scaling these to the yearly energy production assumed for the present study, as was done previously for radioiodine, particulate releases varying from about 0.06 to 2 Ci/yr are estimated for BWR plants and 0 to 0.007 Ci/yr for PWR plants.

Direct and Skyshine Radiation

Although the radionuclides N^{13}, N^{16}, and F^{18} appear in the effluent gases, their contribution is small compared to the other gaseous radionuclides. However, in boiling water reactors N^{16} is a source of off-site radiation which may have environmental significance. The N^{16} in the reactor coolant follows the steam through the external steam separator, piping, turbine, and condenser, and forms a distributed source of 6.13-Mev gammas throughout this circuit. In some plants no biological shielding is provided around the turbine and steam piping; in some plants only peripheral shadow shielding is provided. Consequently, the N^{16} decay gammas can penetrate through weakly attenuating structures to the site boundary.

Upwardly directed N^{16} decay gammas undergo Compton scattering with air, resulting in lower-energy scattered gammas reaching the site boundary. In some BWR installations this direct and "skyshine" radiation could be a principal contributor to off-site radiation exposures at the site boundary, once the exposures from radionuclide effluents are reduced to the levels proposed in 10 CFR 50 Appendix I.

Tritium in Liquid Effluents

Reported releases(18) of tritium in BWR liquid effluents for 1971, scaled according to the energy production of a model 1000 Mw(e) plant, agree well with the present(17) estimates of 20 Ci/yr for a BWR plant. However, for the PWR plants there are wide variations in the reported tritium in liquid effluents. The 1971 data for PWR plants and their extrapolation to a model 1000 Mw(e) plant at 100% load factor, are listed on Table 2.7.

Table 2.7

Tritium in Liquid Effluents for Pressurized-Water

Nuclear Power Plants, Extrapolated to 1000 MW(e)

Thermal power[a] MW(t)	Thermal energy produced[a] MW-days	Reported tritium release in liquid effluents[a] curies/yr	Tritium release extrapolated to 1,000 x 10[illegible] MW-days[b] curies/yr
600	255,000	1,800	9,300
615	72,000	75	6,600
1,300	352,000	59	400
1,065	550,000	5,000	11,600
2,300	377,000	770	400
1,500	418,000	355	385
1,347	433,000	4,650	12,600

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[a] AEC, Report on Releases of Radioactivity in Effluents from Nuclear Power Plants for 1971, Directorate of Regulatory Operations, December, 1972.

[b] Corresponding to 1000 MW(e), 33 thermal efficiency, 80% load factor, 1-yr operation.

These variations in tritium in liquid effluents may result in part from variations in the extent to which neutrons are absorbed in soluble boron controls, as well as in solid boron. For example, a detailed estimate(10) of the rate of release of tritium to reactor coolant for a 1000 Mw(e) PWR nuclear plant operating with an equilibrium fuel cycle is given in Table 2.6

Table 2.6

Tritium Release to Coolant of PWR Plant Equilibrium Fuel Cycle(10)

	Expected release of tritium to coolant, curies/yr
ternary fission	110
burnable poison rods	10
control rods	410
soluble poison boron in reactor coolant	550
Li^7 reaction	11
Li^6 reaction	8
deuterium reaction	1
	1100

The startup cycles require more control poison and may result in a rate of tritium production in the coolant greater than that listed above(10). Variations in tritium release may also be attributable to the metal used for fuel cladding. Older PWR plants, which have stainless steel fuel cladding instead of zircaloy, would be expected to have greater releases of tritium to the coolant and to the environment.

A liquid release of 400 Ci/yr of tritium, as is assumed here for the PWR(17), may be a problem in some installations, depending upon the type of waste heat rejection system which is used. The liquid radioactive wastes are normally discharged into the cooling water returned from the power plant to the environment, so the concentration of tritium in the exit liquid effluent is the tritium production rate divided by the coolant flow rate. For once-through cooling, with a temperature rise of 18°F, the coolant stream leaves a light-water nuclear plant at a flow rate of 880,000 gal/min, so that the 400 Ci/yr of released tritium dilutes to an average concentration of 2.3 x 10^{-7} microcuries/ml. This is considerably lower than the maximum permissible concentration of 3 x 10^{-3} microcuries/ml for tritium in water from 10 CFR 20, and it is lower than the tritium design objective of 5 x 10^{-6} microcuries/ml proposed in Appendix I of 10 CFR 50.

With evaporative cooling the rate of discharge of blowdown water to the surroundings is typically about one hundred times lower, e.g., 7910 gal/min, resulting in a diluted tritium concentration of 3.1 x 10^{-5} microcuries/ml, as shown in Table 2.9. If the waste tritium is injected directly into the cooling water which circulates between the cooling tower and condenser, much of it will appear as tritiated water vapor in the humidified air leaving the cooling tower. For a water make-up rate of 10,230 gal/min, as shown on the flowsheet, the concentration of tritium

TABLE 2.3

Concentrations of Radionuclides in Liquid Effluents for

Light-Water Nuclear Plant with [illegible] [illegible]

	Yearly release in liquid effluents Ci/yr	Yearly average concentrations in water leaving the plant site[a]		
		Liquid waste discharged into dilution water[b] μCi/cc[d]	Liquid waste discharged into cooling-tower blowdown water[c] μCi/cc	Design-objective concentrations proposed in Appendix I, 10 CFR 50[a] μCi/cc
Tritium				
BWR	90[17]	6.3×10^{-6}	2.4×10^{-6}	5×10^{-6}
PWR	450[17]	31×10^{-6}	12×10^{-6}	5×10^{-6}
Radionuclides other than ^3H	5[16]	3.5×10^{-7}	3.5×10^{-7}	2×10^{-8}

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[a] Prior to dilution in natural bodies of water into which the dilution water is discharged.

[b] Based upon 720 gal/min of water dilution.

[c] Based upon 1930 gal/min of make-up water.

[d] μCi = 10^{-6} Ci.

in the water blowdown leaving the plant would then be reduced to 1.8 x 10^{-6} microcuries/ml, still a factor of 8.4 above the proposed design objectives. Using the atmospheric dilution parameters assumed for Table 8.8, the off-site concentration of tritiated water vapor will be far below the 10 CFR 20 maximum permissible concentration, even without taking into account the further dilution resulting from the mixing of tritiated water vapor with the cooling tower air.

Technology is available to reduce the tritium effluents below the levels indicated in the flowsheet. Reactor coolant water withdrawn for auxiliary processing can be returned to the reactor coolant system, although some increase in tritium concentration in the reactor coolant and in the gaseous effluents will result(17). Although expensive, isotope separation(3) can remove tritium before the process water from the liquid waste management system is discharged as liquid effluent.

Other Radionuclides in Liquid Effluents

A representative estimate(18) of the yearly quantities of radionuclides other than tritium which appear in the liquid wastes to be treated by the radioactive liquid waste management system for a 1000 Mw(e) pressurized water reactor is given in Table 8.10. The function of the waste management system is principally that of concentrating these non-volatile radionuclides so that they can be encapsulated or cast into solids and shipped for permanent storage. Evaporator condensates still contain finite carryover of radionuclides, but the radionuclide content of the distillate can be further reduced by ion exchange.

Table 2.10

Estimated Yearly Quantities of Radionuclides, Other than Tritium, In Liquid Wastes Collected for Processing and Conversion to Solids, 1000 MW(e) PWR(10)

	Ci/yr		Ci/yr
Cr^{51}	0.01	Nb^{95}	1.70
Mn^{54}	1.00	Mo^{99}	10,000
Mn^{56}	27.0	Te^{132}	705
Fe^{59}	1.00	I^{131}	6,060
Co^{58}	31.0	I^{132}	295
Co^{60}	3.00	I^{133}	5,400
Sr^{89}	0.07	I^{134}	22.7
Sr^{90}	0.00	I^{135}	2,740
Sr^{91}	2.02	Cs^{134}	914
Y^{90}	1.10	Cs^{136}	88.0
Y^{91}	22.5	Cs^{137}	4,820
Y^{92}	5.40	Ba^{140}	2.40
Zr^{95}	1.70	La^{140}	2.47
Zr^{97}	1.14	Ce^{144}	0.23

Total Activity 38,300 Ci/yr

According to the proposed Appendix I, 10 CFR 50, design objectives, the radioactive liquid waste management system should be capable of reducing the yearly release of non-tritium radionuclides to 5 Ci/yr or less, and this appears attainable with evaporation and ion exchange. Appendix I further proposes a design-objective concentration of non-tritium radionuclides in the liquid effluents from the plant, prior to dilution of these effluents in natural bodies of water, of 2×10^{-8} microcuries/ml. This is easily attainable with once-through cooling, where dilution of 5 Ci/yr in discharge water flowing at 966,000 gal/min (cf. Section 6.1) results in a discharge concentration of 2.6×10^{-9} microcuries/ml. However, as in the case of tritium, operating with evaporative cooling results in less discharge water for dilution of the liquid effluents. For the water blowdown rate of 7010 gal/min for the evaporative cooling tower shown on the flowsheet (cf. Section 6.2), the discharge of 5 Ci/yr would result in a discharge concentration of 3.6×10^{-7} microcuries/ml, as shown in Table 2.9. Further treatment of the process waste to reduce the non-tritium liquid radionuclide discharge to about 0.3 Ci/yr would be required in this example for evaporative cooling.

The reported non-tritium liquid radionuclide releases for 1971(18) are listed in Table 2.11.

Table 6.11

Non-Tritium Radionuclides in Liquid Effluents for Light-Water Nuclear Power Plants Reported for 1971

	thermal power[a] Mw(t)	thermal energy produced[a] Mw-days	reported non-tritium liquid release[a] curies/yr
BWR			
	700	99,000	9.2
	1670	161,000	0.014
	1850	361,000	22.2
	1930	486,000	12.1
	2011	475,000	16.7
	2 x 2527	613,000	23.0
PWR			
	600	208,000	0.012
	615	120,100	61.1
	1300	352,000	0.93
	1825	556,000	5.00
	2200	387,000	0.72
	1518	416,000	0.16
	1347	418,000	1.04

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[a] USAEC, Report on Releases of Radioactivity in Effluents from Nuclear Power Plants for 1971, Directorate of Regulatory Operations, Decemb..., 1972.

Non-Radiological Chemical Releases

Chemical releases are characteristic of those involved in the boiler water treatment system of a steam power plant (cf. Chapter 3). There are additional chemical releases involved in the water treatment systems for plant cooling water (cf. Section 6.2). Thermal releases to surface water and the release of large quantities of humidified air, airborne liquid drift, the concentration of dissolved solids by evaporative cooling systems, and environmental and land-use quantities associated with other possible heat-rejection systems appropriate to light-water nuclear power plants are discussed in Chapter 6.

2.6 Shipment of Irradiated Fuel and Solid Radioactive Wastes

Prior to shipment, the irradiated nuclear fuel removed yearly from the core of a light-water reactor is stored at the nuclear power plant site for about 150 days to allow time for decay of 8.05-day I^{131} and to allow for decay of 6.75-day U^{237} so that its radioactivity level in the uranium recovered from fuel reprocessing will be comparable to the radioactivity of natural uranium(3). Shipment of the shielded irradiated fuel to the reprocessing plant involves, in normal accident-free operation, only very small exposures from gamma radiation penetrating through the shield of the shipping container. No other environmental effects from shipping, in normal operations, are identified in typical environmental impact reports(20). Although possible releases of radionuclides from some classes of postulated shipping accidents are considered in typical environmental impact reports, consideration of these accidents and other accidental environmental releases throughout the nuclear fuel cycle is beyond the scope of the present study (cf. Section 2.12).

2.9 Fuel Reprocessing

Irradiated fuel is reprocessed for the purpose of recovering the contained plutonium and uranium, which have significant monetary value as fuel. If recovery of the plutonium and uranium were not economically essential, the solid irradiated fuel and its contained fission products could be stored as high-level wastes. Metal-clad UO_2 fuel rods are, in fact, an excellent physical form for long and safe storage of the high-level, long-lived radioactive fission products, plutonium, and other transuranic elements present in irradiated fuel.

Fuel reprocessing technology involves chopping the fuel rods into pieces, separating the radioactive cladding hulls from the UO_2 fuel, dissolving the UO_2 in acid, and performing chemical separation by liquid-liquid extraction and ion exchange to yield an aqueous stream of purified uranyl nitrate ($UO_2(NO_3)_2$), an aqueous stream of purified plutonium nitrate ($Pu(NO_3)_4$), and an aqueous stream of dissolved and suspended fission-product salts. In some processes part of the purification is accomplished by fluoride distillation.

In the present flowsheet the uranium product is then converted to uranium hexafluoride for recycle to the isotope separation plant. The plutonium product is stored (cf. Section 2.13). The high-level fission product aqueous stream is either stored in large tanks for up to 5 years, or it is converted immediately into a dry chemical form and cast into an inert solid matrix. Within ten years after separation the high-level radioactive wastes are to be shipped, in converted solid form, to a federal repository for long-term storage(21).

The yearly rates at which radioactivity in the irradiated fuel from a 1000 Mw(e) light-water nuclear plant appears at the reprocessing plant, after 180 days cooling, are listed in the fifth column of Table 2.4. When the fuel is dissolved all of the noble-gas fission products, containing 373,000 Ci/yr of 10.76-yr Kr^{85}, are discharged to the atmosphere through a stack tall enough to obtain adequate atmospheric dispersion before the discharge gas reaches the site boundary.

The tritium in the irradiated fuel forms tritiated water upon fuel dissolution. About 86% of this is evolved as tritiated water vapor, and the remaining 14% is ultimately discharged with the liquid effluents into the surface water leaving the plant site(4). The ultimate disposition of the additional tritium formed in solid boron control absorbers and the possible release of portions thereof when the control absorbers are removed from the reactor and stored or processed, is not shown on this flowsheet.

The indicated iodine release is based upon data in reference (2), using an iodine decontamination factor of 1000 for the iodine scrubber system.

The iodine release of 3.7 Ci/yr of Ru^{106} in the liquid wastes, 0.8 Ci/yr of other airborne fission products, and 0.0037 Ci/yr of transuranics in gaseous effluents are derived from data in reference (4).

scaled to the uranium throughput shown on the flowsheet. Additional environmental quantities, expressed as quantities per tonne of uranium throughput, are listed in Table 2.10, derived from data on a model plant with a capacity of 2.5 tonnes/day(4).

The volumes of high level wastes, intermediate level liquid wastes, low level liquid wastes, and solid wastes shown on the flowsheet are derived from data in reference (2). Plutonium remaining with the high level wastes is 0.5% of the total plutonium processed(2).

Solid wastes of lower activity result from off-gas cleanup, solvent washes, spent ion exchange resin, and other cleanup and decontamination operations. These wastes, principally in the form of nitrate and nitrite solutions, are concentrated and crystallized as salt and stored in metal containers inside a concrete vault. Typically, these wastes contain about 8 grams of plutonium, 0.2 kilograms uranium, and less than 0.01% of the total fission products per tonne of uranium processes(23). Using data on this flowsheet, the yearly quantities for the 1000 Mw(e) nuclear plant are 8000 Ci of plutonium, less than 13,000 Ci of fission products, and 0.002 Ci of uranium.

Lower-level dry chemical wastes resulting from fluorination operations are stored as dry fluorides of aluminum, sodium, and magnesium in a steel lined vault. These wastes contain about 3 grams of plutonium, 1.75 kilograms of uranium, and less than 0.01% of the fission products per tonne of uranium processed(23). This corresponds to yearly quantities for the 1000 Mw(e) nuclear plant of 1370 Ci of plutonium,

Table 2.12

Environmental Quantities for Fuel Reprocessing*

Natural Resource Use(4)	
Land, acres per 1 Te U/yr capacity	
Temporarily committed	0.11
Undisturbed area	0.10
Disturbed area	0.01
Permanently committed	0.001
Water, gal/Te U(4)	
Discharged to air	1.1×10^6
Discharged to water	1.7×10^6
Total	2.8×10^6
Electrical Energy(4), kwh/Te U	1.08×10^4
Effluents	
Chemical(4), Te/Te U	
Combustion Gases	
SO_x	0.19(a)
NO_x	0.20(b)
hydrocarbons	0.0006(a)
CO	0.0011(a)
F	0.0014
Liquids	
Na^+	0.15
Cl^-	0.006
$SO_4^=$	0.01
NO_3^-	0.02
Radiological, Ci/Te U	
Gases (including entrained matter)	
Kr^{85}	11,000(c)
H^3	690(c)
I^{129}	2×10^{-5} (c)
I^{131}	1.01×10^{-3} (c)
other fission products(4)	0.028
transuranics(4)	1.1×10^{-4}
Liquids	
H^3	27.6
Ru^{106} (4)	0.11
Thermal, kwh/Te U(4)	610

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*Environmental release quantities are obtained by multiplying the above data by the uranium throughput.

(a) Estimated effluent gases from combustion of equivalent coal for power generation.

(b) 93% of total is estimated effluent gas from combustion of equivalent coal for power generation(8).

(c) Calculated from data in Table 2.4.

0.08 Ci of uranium, and less than 13,000 Ci of fission products.

It should be recognized that the indicated releases and process quantities in fuel reprocessing indicated on the flowsheet are those resulting only from the fuel from the reference 1000 MW(e) light water nuclear plant. Commercial fuel reprocessing plants are now designed to handle uranium throughputs from 1 to 4 tonnes per day(4), and even larger throughputs are calculated for the most economical operations. Therefore, the total releases from the fuel reprocessing plant will be greater than the quantities indicated on the flowsheet. For example, a reprocessing plant with a capacity of 4 Te U/day could process the fuel from 40 light water nuclear plants operating as shown in the flowsheet, all operations at 100% load factor.

There are several technologies which could be applied to reduce the radionuclide effluents in fuel reprocessing, if such reduction were found to be necessary or desirable.* For example, tritium can be removed as a gas, rather than being incorporated in aqueous dissolver solutions, by heating sheared fuel in air or oxygen prior to dissolution. Krypton can be removed by cryogenic distillation or by selective absorption in chilled organic, followed by storage in gas cylinders. Iodine can be further removed by scrubbing the dissolver off-gases with concentrated nitric acid, oxidizing the iodine to solid I_2O_5, followed by further treatment of the off-gases with a charcoal scrubber or with a bed of silver-deposited zeolite. These operations concentrate on recovery of radionuclides from the primary sources of gaseous and liquid effluents. It would be expected that secondary sources of iodine, such as process cell ventilation air, building ventilation air, etc., could also contribute to iodine releases (see discussion of gaseous radioiodine releases in Section 8.7).

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*The AEC has published proposed numerical guides specifying radionuclide releases from light water nuclear power plants which meet the provision of the 10 CFR 50 regulations that radiation exposures shall be "as low as practicable." No such guides have been issued for other operations in the nuclear fuel cycle.

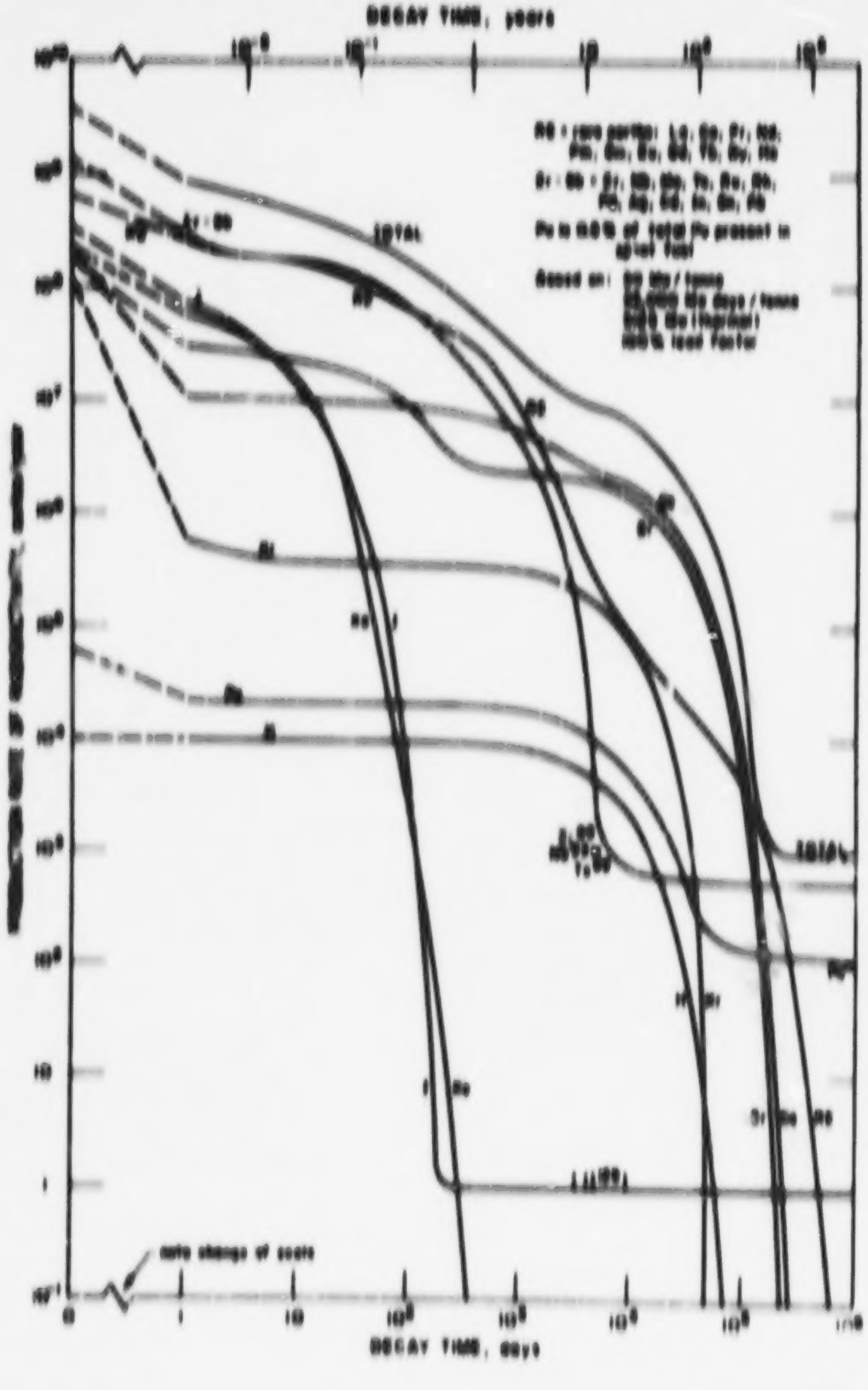
8.10 Management of High-Level Radioactive Wastes

The radioactivity associated with the fission products produced by the 1000 Mw(e) light-water nuclear power plant in one year of operation as a function of elapsed time since the irradiated fuel was discharged from the reactor, is shown in Figure 8.8. Data for this figure were calculated on the assumption that 0.5% of the plutonium in the discharge fuel remains with the high-level fission product wastes(8). It is apparent that significant quantities of radioactivity remain after hundreds of years of storage, so the waste-management program must provide for isolation of these wastes from the environment.

The solidified and encapsulated high level wastes are to be shipped to a federal repository for interim or perpetual storage within 10 years after they are separated in the chemical reprocessing plant. Typically, the wastes would be cast in a solid matrix in the form of steel-clad cylinders 6 in. in diameter and 8 to 10 ft. long(8,24). One cubic foot of the solid matrix is allotted to the fission products resulting from 10,000 Mw-days of thermal energy production in the reactor(8), resulting

Figure [illegible]

Radioactivity Produced in One Year by a 1000 Mw(e) Light Water Nuclear Power Plant



in 114 cu.ft./yr. of solid high-level matrix containing the high-level fission products from the 1000 Mw(e) light water nuclear power plant. This is equivalent to 60 waste containers per year. Each waste container, containing 10-year old fission products, generates about 5000 watts of thermal power.

Two approaches to long-term isolation are considered[(84)]. One involves disposal of the wastes in some form and location such that the long term integrity of each waste container, and continual surveillance thereof, would be unnecessary. Continual isolation from the environment would be obtained by the favorable retention properties of the surrounding natural media. Such disposal would involve no plans or intent to recover the emplaced high-level wastes. Disposal in bedded salt deposits is an example of this approach. Another approach involves retrievable storage, whereby the long-term integrity of the storage container is to be preserved and is to be verified by periodic monitoring, with provisions for retrieving and, if necessary, reconstituting the wastes if monitoring indicates the possible deterioration of an individual container or of any of the several other additional isolation barriers that are provided. This is characteristic of the storage of fission-product waste canisters in water-filled canals in a Federal repository, which would be designed and constructed for this purpose. The present AEC plans for waste management appear to allow for both approaches, with individual surveillance storage as a possible interim method until uncertainties associated with non-surveillance disposal are resolved.

Perpetual storage in bedded salt would require about 1.0 acres per year for the amount of fission-product high-level wastes produced in the 1000 Mw(e) light-water nuclear power plant[8]. If canal storage is used, data in ORNL-4451[8] lead to the calculation that about 60 sq.ft./yr. of canal storage would be required for the solidified wastes from the 1000 Mw(e) nuclear plant.

The AEC now contemplates[4,22] a storage facility located in some remote area, constructed for a service life of 100 years. The massive structure would provide radiation shielding, and the structure could be kept serviceable beyond its design lifetime. The overall site would occupy about 1000 acres, of which about 20 acres would be devoted to an initial module capable of storing the annual high-level wastes from 200 1000 Mw(e) light-water nuclear power plants.

Storage of high-level wastes in bedded salt is expected to result in only small releases of radionuclides to the environment. The projected radiological and chemical releases include gaseous Kr^{85}, H^{3}, and He that result from radioactive decay; Rn^{222} and Rn^{220} emitted by radioactive sources occurring naturally in the underground salt formation; H_2 and HCl resulting from salt decomposition, corrosion, electrolysis, and radiolysis; diesel exhaust fumes; and salt particles[24].

Average annual release rates[24] projected for an embedded-salt storage facility are tabulated in Table 2.13.

The embedded salt facility was designed to handle a yearly input of 21,000 containers of high-level solidified waste by the year 2000.

Table 8.13

Estimated Release Rates for an Embedded Salt High-Level Waste Storage Facility, Full-Scale Operation(24)

Radiological, Ci/yr.

high-level waste particles	0.007
alpha waste particles	0.04
Kr^{85} (from spontaneous fission)	0.014
H^3 (from spontaneous fission)	0.0009
Rn^{222} (natural sources)	0.9
Rn^{220} (natural sources)	0.04

Chemical, s.cu.ft./min.

H_2 (corrosion, radiolysis, electrolysis)	37
He (alpha decay)	0.001
HCl (brine decomposition	0.07
CO_2 (diesel exhaust)	60
CO (diesel exhaust)	0.05
NO_2 (diesel exhaust)	0.05
SO_2 (diesel exhaust)	0.03
CH_2O (diesel exhaust)	0.0007

Other

Soot (diesel exhaust)	2 lb/yr.
Salt particles	5 lb/yr.

with a total accumulated inventory of 200,000 containers. It would appear, therefore, that the projections in Table 2.13 for the effluents for the entire facility at full-scale operation would be attributable to the accumulated output of several hundred 1000 Mw(e) nuclear power plants or to the yearly output of several thousand plants. Therefore, the effluents resulting from storage of high level wastes from the reference 1000 Mw(e) nuclear plant would be several orders of magnitude lower than those listed in Table 2.13.

2.11 Accidental Environmental Releases

Additional environmental impact and risk can result from radiological and chemical releases from various possible accidents through the fuel cycle. Accidents of environmental significance range over a broad spectrum, from small accidental releases of almost routine occurrence to accidents of low probability but serious consequence. The environmental consequence alone is determined by the magnitude of a given accidental release and by its biological and ecological effect. However, for a given accident, the environmental significance and environmental risk are not determinable unless the accident consequence and accident probability are both known.

It is apparent that there will be some accidents near the low-consequence end of the accident spectrum which are of low enough consequence to involve negligible risk, even if the accident were assumed to occur with certainty, i.e., with a probability of unity. This is characteristic of the accidental-release estimates that can be obtained from present environmental impact statements. These estimates are useful in identifying the sources and magnitude of some of the accidental releases that might be more likely to occur. Elsewhere there are also estimates of releases from other accidents, including accidents* of high consequence and undoubtedly low probability. However, these release estimates for high-consequence accidents are not accompanied by estimates of accident probabilities that can be reasonably associated with these releases. Therefore, accidental release estimates now available in the public literature do not yet provide a data base for the objective and comprehensive analysis of the environmental significance of accidental environmental releases. High-consequence release estimates without associated probabilities, and low-consequence estimates alone, are insufficient and misleading for comprehensive determination of environmental impact. The difficulties of estimating accident probability and accidental risks, and the questionable and invalid assumptions and conclusions that can arise as a result of this lack of information, are considered in the following paragraphs.

Various estimates of probabilities of nuclear reactor accidents have appeared in the literature(27,28,29,30) but are of questionable validity because of the lack of meaningful and reliable input data on failure mechanisms and failure rates, because of the very limited extent to which real and possible failure mechanisms have been considered, and because of idealized and optimistic assumptions of uncorrelated failure modes made in calculating probabilities of multi-event accidents.

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*Examples are the loss-of-coolant design basis accident, and its associated radiological releases, as well as the many other accidents and associated releases, considered in the safety analysis of nuclear power plants. Accidents with greater releases are also possible(26). There are similar examples throughout much of the nuclear fuel cycle(26).

Correlated failure modes result, for example, when the operation of a particular component or system is adversely affected by failure of nearby or surrounding equipment or by failure of other equipment and systems to which it is attached. For example, an otherwise reliable plumbing system may be damaged and become inoperative if the surrounding building structure fails. To idealize each component and system as failing only by the statistical occurrence of that item alone, as in fault-tree analysis incorporating the assumption of independent random probability of failure of each component, results in simple mathematical techniques but in idealistically low probabilities of multi-event accidents. Techniques are available to take correlated failures into account, and these should be applied. However, because of the lack of sufficiently reliable input data, accurate and definitive probability and risk analysis will still not be possible for low-probability high-risk accidents. Therefore, one must also know the bounds of the probability estimates before meaningful conclusions as to risks can be made.

Present estimates of accident probabilities that have appeared in the literature do not, therefore, define an upper bound or even a lower bound to probabilities and risks. The bounds of the estimates are unknown, the input data are of doubtful reliability for analysis of these low-probability events, and the flaws and assumptions in analytical techniques lead to probability estimates which can be over-optimistically low.

Although estimating meaningful accident probabilities is extremely difficult, it is less difficult to estimate the consequences of a postulated accident and then to determine how low the accident probability must be for the risk to be reasonable. By "reasonable" we mean that the risk be of the same order of magnitude as other calculable risks to which society is frequently exposed, such as driving automobiles. Such analysis shows that for some high-consequence accidents the accident probability must be less than one such accident in several hundred thousand years of reactor operation. Unfortunately, the excellent record of operating experience for nuclear power plants and for other facilities in the nuclear fuel cycle is statistically insignificant for the purpose of confirming the expected low probabilities of high-consequence accidents. These probabilities and their associated risks are unknowable by experience. Therefore, risk analysis for the low-probability accidents must rest upon prediction, but the prediction must result from a far more detailed and careful analysis and with more reliable and meaningful input data than has occurred at present.

Before any conclusion can be reached that the probabilities of releases from high-consequence accidents are so low as to be meaningless for the purpose of analyzing impact, quantitative estimates of accident probabilities and quantitative estimates of risks are needed. In the absence of such probability and risk estimates* a conclusion as to which accidents have environmental significance is meaningless. It has been shown(30) that some accident probabilities suggested as being so low as to be insignificant can actually involve risks and environmental impacts significantly greater than from normal operation. Quantification of accidental releases and associated accident probabilities, and quantification of risks, are necessary before meaningful conclusions can be drawn concerning the environmental significance of the broad spectrum of possible accidents. The necessary data are not yet available.

2.12 Effect of Plutonium Utilization

For the purpose of the present study it is assumed that the plutonium recovered from the discharge fuel is stored. This is characteristic of the present mode of operation of light water reactors, but it is an unrealistic assumption for even the present reactors over their operating life of 30 to 40 years. The 0.298 Te of plutonium recovered yearly from the discharge fuel contains 0.208 Te of fissile plutonium.

This recovered plutonium could be recycled as makeup fuel for this same reactor by blending it with uranium, thereby decreasing the required enrichment of U^{235} in the makeup uranium. Alternatively, the plutonium recovered from the discharge fuel of several water reactors operating without plutonium recycle could be blended with natural uranium to form the makeup fuel for other water reactors. On the basis of these schemes the fuel value of plutonium has been estimated to be about $10 per gram of fissile plutonium(32). Thus, the plutonium recovered yearly from the discharge fuel in the present flowsheet is worth about $2 million/yr. in a water-reactor nuclear power economy. This compares with $61 million/yr. as the value of the total electrical energy produced, assuming a generating cost of 8 mills per kwh(e) and a load factor of 100%. In fact, it is the fuel value of the recovered plutonium which is the principal justification for reprocessing discharge fuel. There is indeed economic gain from the recovered uranium. However, at an enrichment of 0.780% U^{235}, the discharge uranium is worth about $30/kg. in the form of UF_6. The value of the uranium recovered from fuel reprocessing for the 1000 Mw(e) nuclear plant is about $920,000/yr. as compared with the plutonium value of about $2 million/yr. Clearly, utilization of the recovered plutonium is significant to the economy of these water reactors. The plutonium must be used, and its use will involve new environmental considerations.

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*Although the idealized estimates of accident probabilities which have recently appeared in the literature(27,28,29) are quoted in some environmental impact statements as background information, they have not been used as the basis for assessing risk limits of high-consequence accidents for the purpose of environmental impact assessment(31).

There are several alternative ways of utilizing the plutonium recovered from water-reactor fuel. Fissile plutonium is more valuable as a fuel for fast breeder reactors because of its more favorable neutronic properties in a fast reactor spectrum. Although a fast-breeder reactor can be fueled solely on natural uranium makeup when it has reached its equilibrium fuel cycle, a significant inventory of plutonium is needed to provide the initial fuel loading and startup reloads for such reactors. This should provide the most beneficial use of plutonium from water reactors once economical fast-breeder power reactors are available for new construction to meet the expanding power demands. However, the time schedule for development of economical fast-breeder power reactors cannot result in a significant demand for water-reactor plutonium as fast-breeder startup fuel until the latter part of this century. Assuming introduction of the first commercial fast breeder reactors in the mid-1980's, plutonium inventories aimed at this use will not become a significant factor in the plutonium market before the early 1990's[33]. Storage of plutonium for such a long period and consequent deferral of income from plutonium values would be extremely expensive. In the continued absence of any military market for plutonium recovered from water-reactor fuel, it is clear that there is an enormous financial incentive to utilize this plutonium as water reactor fuel. Recycle of plutonium in light-water reactors is an economic necessity[33], and the environmental consequences of plutonium recycle are a necessary part of a complete analysis of the light-water reactor fuel cycle.

Plutonium utilization would entail its shipment to a fuel refabrication plant, where it would be chemically converted to the oxide and mixed with uranium oxide. The uranium releases associated with fabrication (cf. Table 2.3) correspond to a total release of 0.05 of the uranium processed. If the 0.286 te of recovered plutonium, with a total radioactivity level of 4.09 x 10^5 Ci*, were fabricated into a UO_2-PuO_2 fuel with the same losses, the plutonium effluents would amount to about

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*This includes radioactivity from decay of Pu^{236}, Pu^{238}, Pu^{239}, Pu^{240}, Pu^{241}, and Pu^{242} (cf. Table 7.4). Additional radioactivity is associated with radioactive-decay daughters of Pu^{238} and Pu^{241}, which grow in after fuel reprocessing.

33,000 Ci/yr. Because of the biological hazard of plutonium, it is apparent that fabrication operations involving plutonium fuel must be carried out with process losses several orders of magnitude below those now characteristic of uranium fuel fabrication. At equilibrium, the plutonium concentration in the uranium fuel and the yearly amounts of plutonium handled in the fuel cycle would be several times greater than the amounts shown in the non-recycle flow sheet(32).

Because of the extreme toxicity and radioactivity of plutonium, consideration of the effects of plutonium recycle or of equivalent means of utilizing plutonium as a reactor fuel is an important element in a comprehensive environmental analysis of technologies of electrical power generation. Although such an analysis is an intrinsic part of the comprehensive environmental impact study for the light-water reactor fuel cycle, limitations of time precluded further consideration of the effects of plutonium utilization in water reactors in the present study.

REFERENCES

1. Arnold, E. D., Phoebe-A Code for Calculating Beta and Gamma Activity and Spectra for 235U Fission Products, ORNL-3931, USAEC (July, 1966).

2. Siting of Fuel Reprocessing and Waste Management Facilities, ORNL-4451 (July, 1970), U.S. AEC, Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, 22151.

3. Benedict, M. and T. H. Pigford, Nuclear Chemical Engineering, McGraw Hill, New York (1958).

4. United States Atomic Energy Commission, Environmental Survey of the Nuclear Fuel Cycle, Fuels and Materials Directorate of Licensing, U.S. Atomic Energy Commission, November, 1972.

5. United States Atomic Energy Commission, Draft Detailed Statement on the Environmental Considerations by USAEC, DML, Related to the Proposed Issuance of an Operating License to Humble Oil and Refining Company for the Highland Uranium Mill, USAEC Docket No. 40-8102 (April 19, 1972).

6. Humble Oil and Refining Company, Environmental Report, Highland Uranium Mill, Converse County, Wyoming, Docket No. 40-8102, (July, 1971).

7. Utah International, Inc., Draft Detailed Statement for Highland Uranium Mill, Supplemental Environmental Information Requested by the AEC in letter dated February 11, 1972, Docket No. 40-6622, June 23, 1972.

8. The 1972 World Almanac and Book of Facts, p. 157.

9. Tsivoglou, E. C. and R. L. O'Connell, Waste Guide for the Uranium Milling Industry, Tech. Rept. W62-12, (US PHS R. A. Taft San. Eng. Ctr., Cincinnati, Ohio, 1962).

10. Humble Oil and Refining Co., Response to Agency Comments on Draft Statement, Highland Uranium Mill, USAEC Docket 40-8102 (August, 1972).

11. Kerr-McGee Corporation, Uranium Hexafluoride Plant, Supplemental Applicant's Environmental Report, USAEC Docket No. 40-8027 (June, 1972).

12. United States Atomic Energy Commission, *AEC Data on the Gaseous Diffusion Plants*, ORO-685 (April, 1972).

13. Denton, H. R., *Statement on the Sources of Radioactive Material in Effluents from Light-Water-Cooled Nuclear Power Reactors and the Radwaste Treatment Equipment to Minimize Releases*, U. S. AEC, Docket RM-50-2 (January 19, 1972).

14. Detroit Edison Company, Enrico Fermi Atomic Power Plant, Unit 2, U.S. AEC Docket No. 50-341.

15. U.S. Atomic Energy Commission, 10 CFR 20.

16. U.S. Atomic Energy Commission, *Proposed As Low As Practicable Amendment to 10 CFR 50 Licensing of Production and Utilization Facilities*, Federal Register, Vol. 36, No. 111, June 9, 1971.

17. Rodger, W. A., *Testimony on Behalf of the Consolidated Utility Group*, presented at the AEC Rule-Making Hearing on the Proposed Appendix I to 10 CFR 50, Docket RM-50-2 (April, 1972).

18. *Report on Releases of Radioactivity in Effluents from Nuclear Power Plants for 1971*, Directorate of Regulatory Operations, U. S. Atomic Energy Commission (December, 1972).

19. Pacific Gas and Electric Company, *Preliminary Safety Analysis Report for the Diablo Canyon Nuclear Power Plant*, Unit 2, U.S. AEC, Docket No. 50-323.

20. U.S. Atomic Energy Commission, *Final Environmental Statement Related to Operation of Monticello Nuclear Generating Plant*, Northern States Power Co., Docket No. 50-263 (November, 1972).

21. 10 CFR 50, Appendix F.

22. United States Atomic Energy Commission, *Management of Commercial High Level Wastes*, SECY-2371 (March, 1972).

23. United States Atomic Energy Commission, *Final Environmental Statement Related to Operation of the Midwest Fuel Recovery Plant* by the General Electric Co., Docket No. 50-268 (December, 1972).

24. United States Atomic Energy Commission, *Environmental Statement Radioactive Waste Repository*, Lyons, Kansas (June, 1971).

25. Pigford, T. H., "Study of Behavior of Clouds and Contaminants in the Lower Atmosphere Over the X-25 Area," M.I.T. CPS, Report X-604 (April, 1952). (Declassified

26. Beattie, J. R. and P. M. Bryant, "Radiological Dose Computation," *Nuclear Safety*, 11, (6) 486-491 (November-December, 1970).

27. Otway, H. J. and R. C. Erdmann, "Reactor Siting from a Risk Viewpoint," *Nuclear Engineering and Design*, 13 (1970), 365-376. North-Holland Publishing Co.

28. Starr, C., M. A. Greenfield, and D. F. Hausknecht, "Public Health Risks of Thermal Power Plants," *Nuclear News*, 15, No. 10, 37-45 (October, 1972).

29. Otway, H. J. and R. C. Erdmann, "Risk Estimate for an Urbanized Reactor," *Nuclear Technology*, 12, 173-184 (October, 1971).

30. Pigford, T. H., "Protection of the Public from Radioactivity from Nuclear Power Plants," *Proceedings of the 1971 Symposium on Nuclear Science, I.E.E.E.* (February, 1972).

31. U.S. Atomic Energy Commission Regulatory Staff, Testimony, U.S. AEC Docket No. 50-341.

32. U.S. Atomic Energy Commission, *Potential Nuclear Power Growth Patterns*, Division of Reactor Development and Technology, WASH 1098 (December, 1970).

33. Dawson, F. G., W. C. Astley, J. Haley, J. R. Tomonto, T. Trocki, "Plutonium Utilization in Light-Water Reactors," Proc. U. N. International Conference on the Peaceful Uses of Atomic Energy, Vol. 9, 131-147 (September, 1971).

34. Rubin, J. H., "Evolving U. S. Policies in Radioactive Waste Management," AIF/ANS International Conference, Washington, D.C. (November, 1972).

3. ELECTRICAL POWER GENERATION FROM LOW-SULFUR BITUMINOUS COAL

3.1 Introduction

The coal fired power plant discussed in this Chapter is a "composite" 1000 Mw(e) plant whose characteristics are selected to be representative of modern coal fired units. It is fueled with Eastern bituminous coal containing 1% sulfur, obtained from either open pit or underground mines. The material quantities are different for each mode of coal production. Each of these mining operations involves different material quantities, and each will be considered as an alternate source of supply for the 1000 Mw(e) coal fired power plant. The illustrative fuel cycle flowsheet is shown in Figure 3.1.

There are many uncertainties in the quantities reported in this Chapter due to the general lack of specific and correlated data, the large variety of coal characteristics, and wide variations in mining, processing, and other fuel cycle operations.

3.2 Open Pit Mining

The required quantity of raw coal produced at the mine to supply the power plant fuel for one year is 3.94×10^6 Te. This number is obtained by back-calculating using material balances from the necessary thermal energy at the power plant. For an estimated(1) resource recovery of 80%, the required yearly consumption of in-ground coal resource of 4.93×10^7 Te is estimated.

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

〰▶ ELECTRICAL ENERGY
- - - -▶ AIRBORNE RELEASE
⇨ LIQUID EFFLUENT
➡ SOLID EFFLUENT

To = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keeton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

TEKNEKRON, INC.
BERKELEY, CALIFORNIA

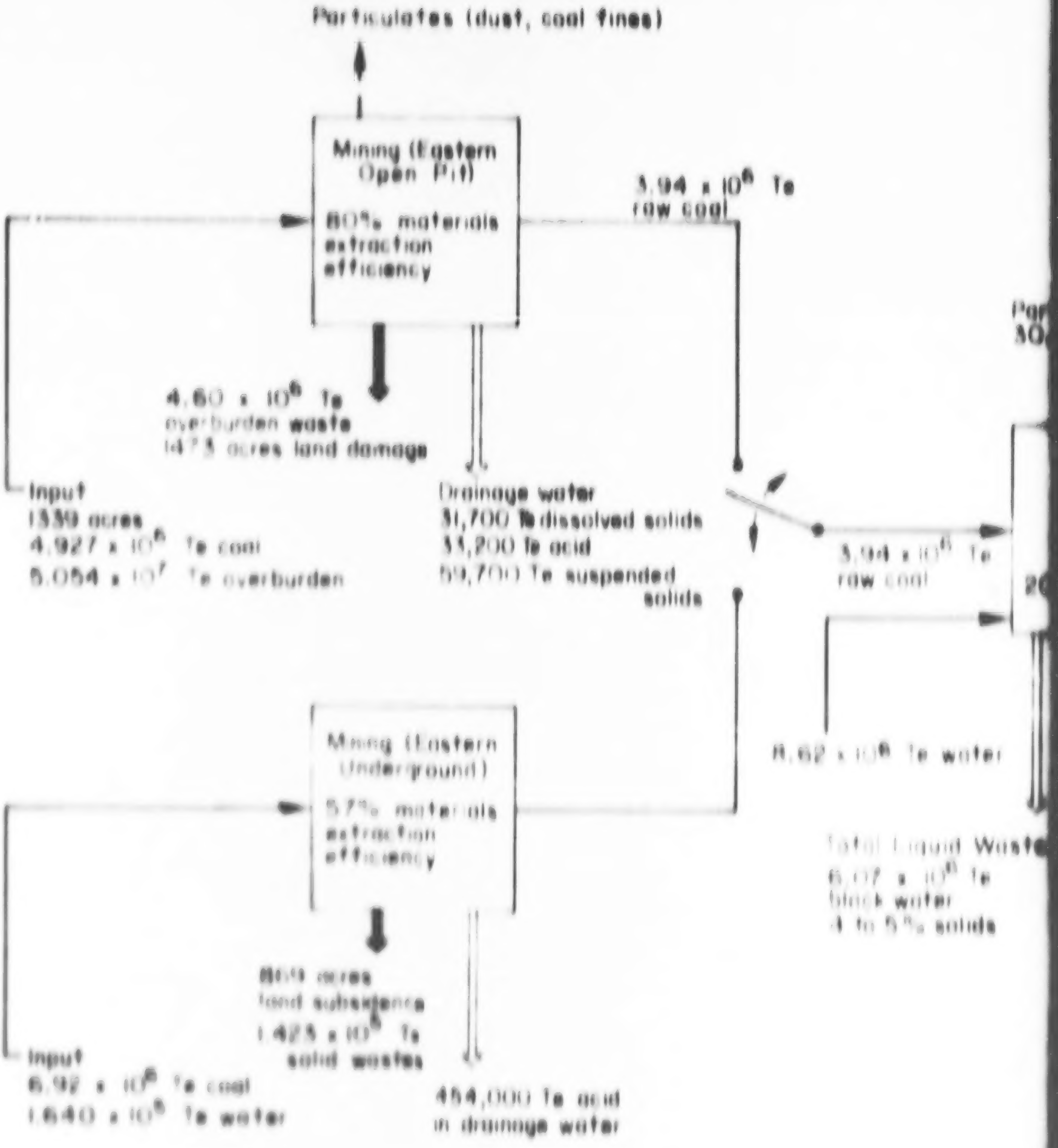
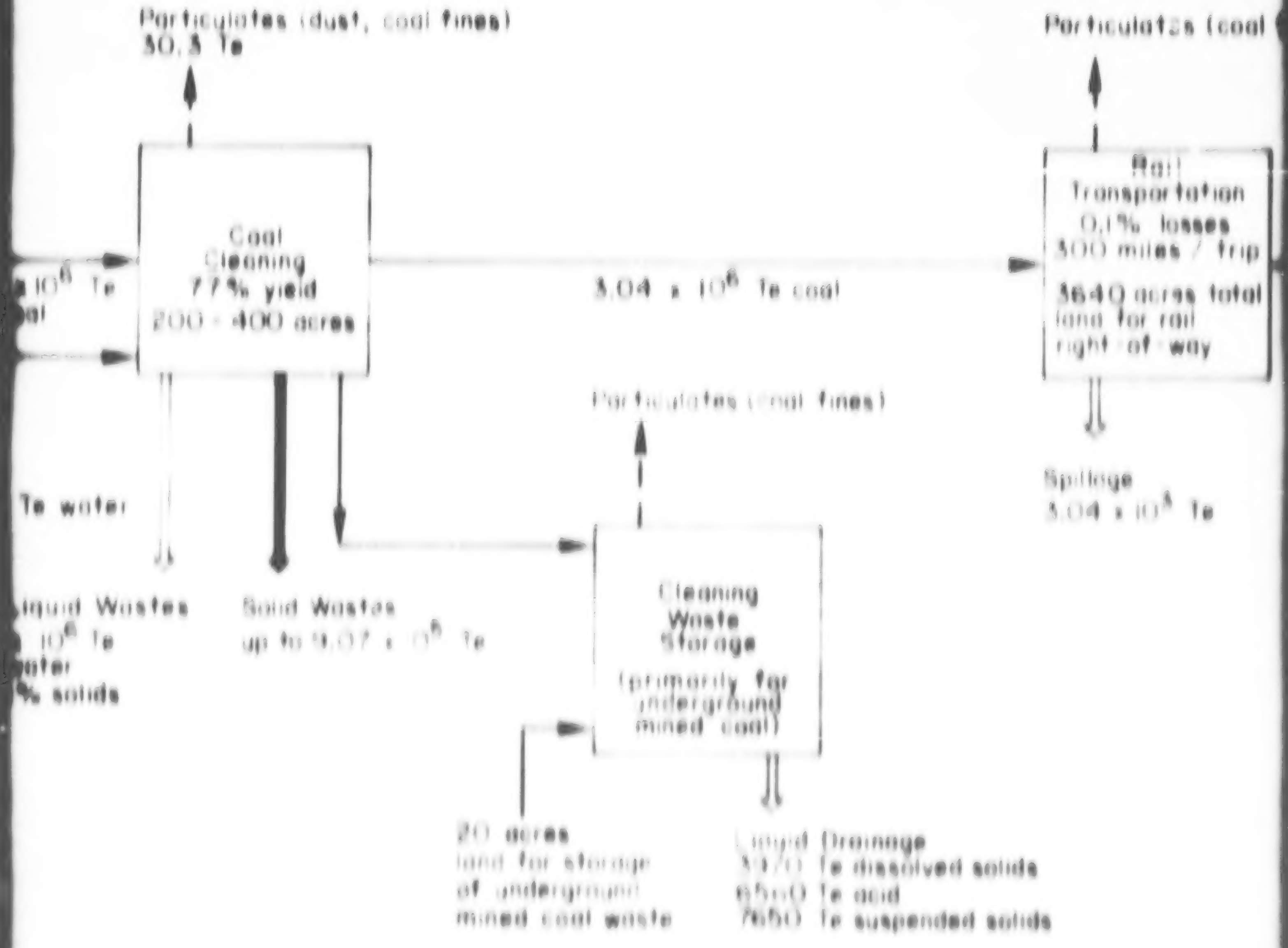

Particulates (dust, coal fines)
Mining (Eastern Open Pit)
80% materials extraction efficiency
3.94 x 10^6 Te raw coal
4.60 x 10^6 Te overburden waste 1473 acres land damage
Input 1339 acres 4.927 x 10^6 Te coal 5.054 x 10^7 Te overburden
Drainage water 31,700 Te dissolved solids 33,200 Te acid 59,700 Te suspended solids
3.94 x 10^6 Te raw coal
Par
SO
20
8.62 x 10^6 Te water
Total Liquid Waste 6.07 x 10^6 Te black water 4 to 5% solids
Mining (Eastern Underground)
57% materials extraction efficiency
869 acres land subsidence 1.425 x 10^6 Te solid wastes
Input 6.92 x 10^6 Te coal 1.640 x 10^5 Te water
454,000 Te acid in drainage water

Figure 3.

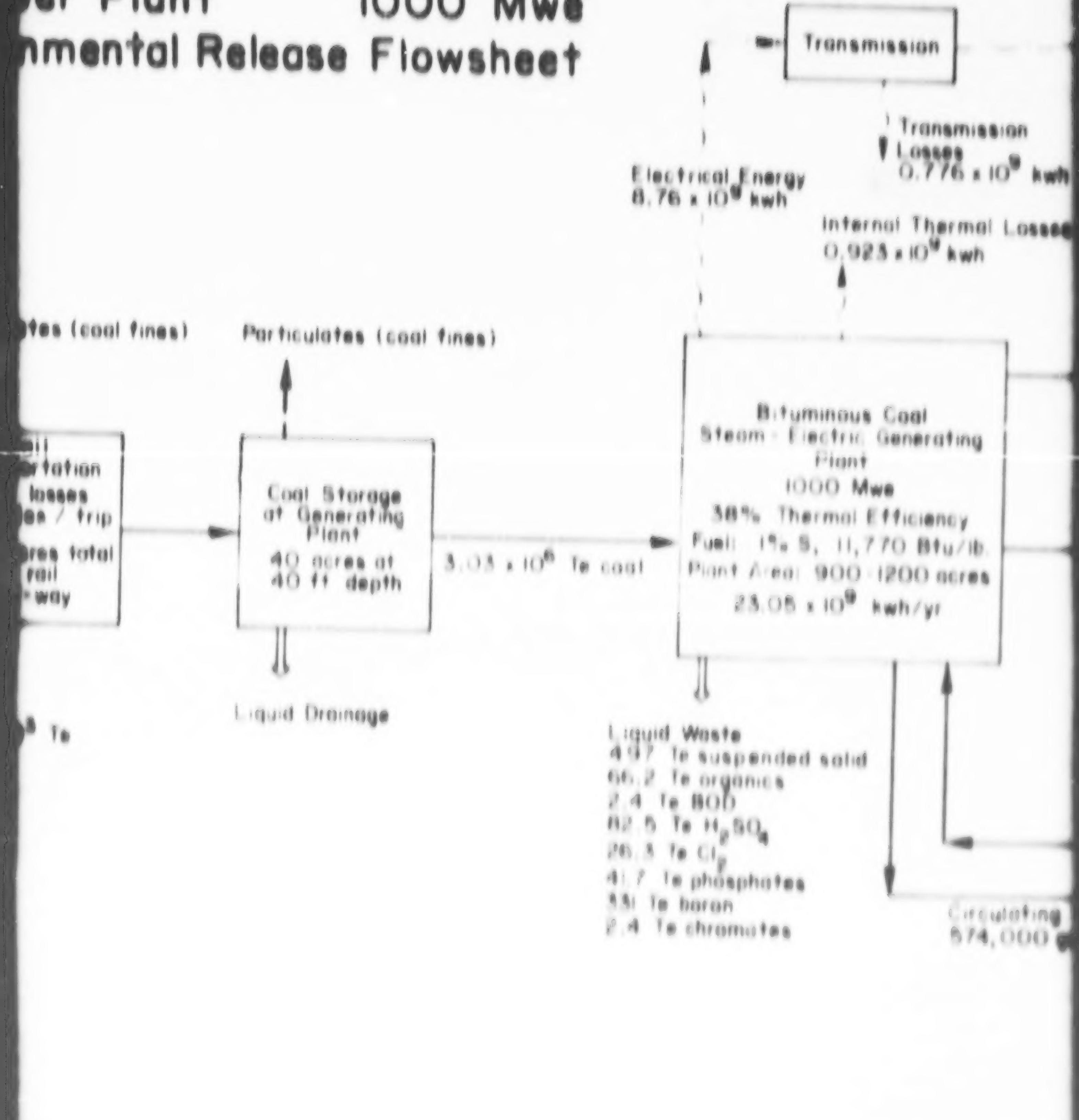
Bituminous Coal Power Pl
Material And Environment

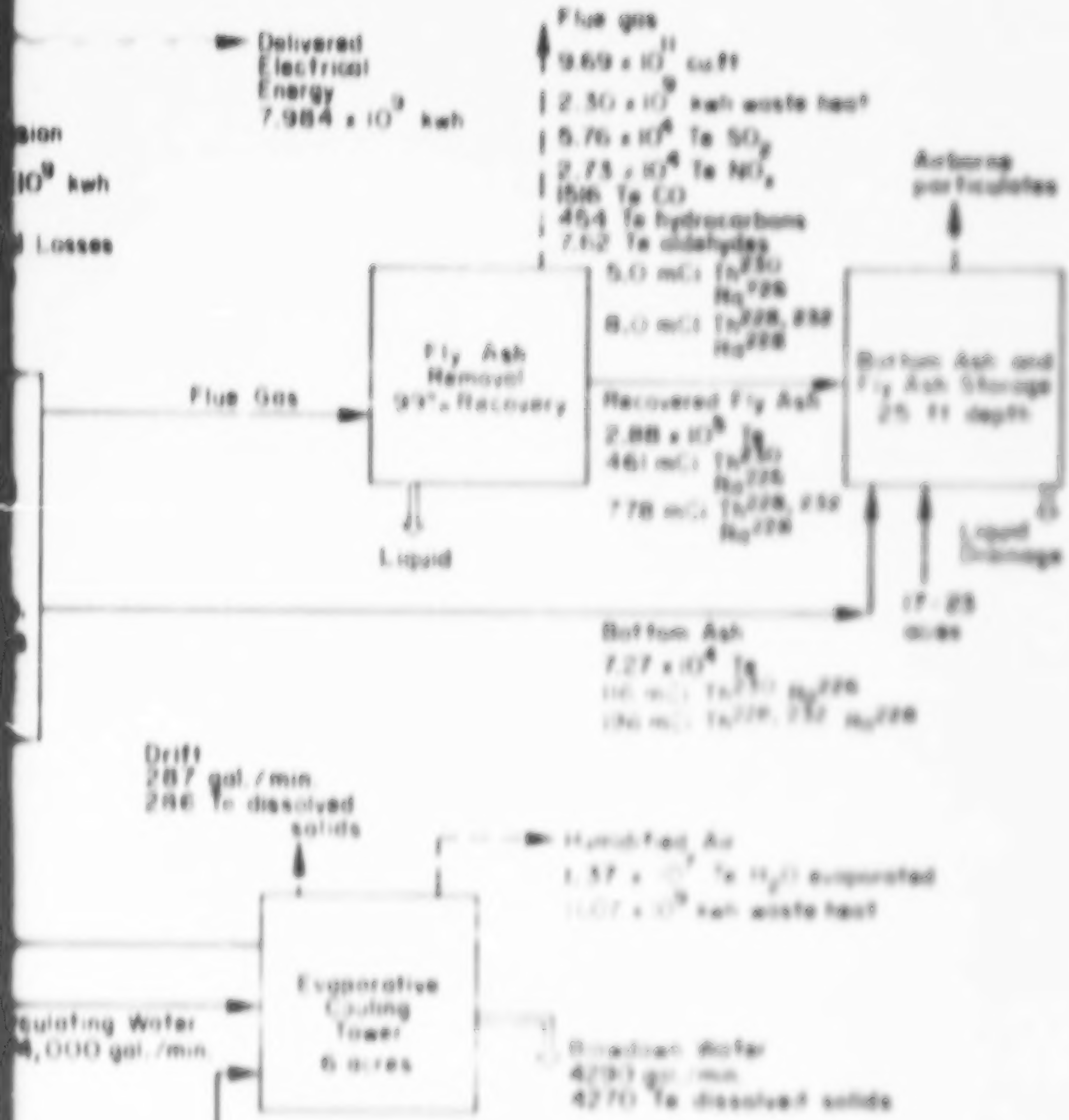


Particulates (dust, coal fines)
30.3 Te
Coal
Cleaning
77% yield
200 - 400 acres
x 10^6 Te
oal
Te water
iquid Wastes
x 10^6 Te
water
% solids
Solid Wastes
up to 9.07 x 10^5 Te
3.04 x 10^6 Te coal
Particulates (coal fines)
Cleaning
Waste
Storage
(primarily for
underground
mined coal)
20 acres
land for storage
of underground
mined coal waste
Liquid Drainage
3970 Te dissolved solids
6560 Te acid
7650 Te suspended solids
Particulates (coal
Rail
Transportation
0.1% losses
300 miles / trip
3640 acres total
land for rail
right-of-way
Spillage
3.04 x 10^3 Te

igure 3.1

er Plant 1000 Mwe
nmental Release Flowsheet


Transmission
Transmission Losses 0.776 x 10^9 kwh
Electrical Energy 8.76 x 10^9 kwh
Internal Thermal Losse
0.923 x 10^9 kwh
tes (coal fines)
Particulates (coal fines)
ail
rtation
losses
es / trip
res total
rail
-way
Coal Storage at Generating Plant
40 acres at 40 ft depth
3.03 x 10^6 Te coal
Bituminous Coal Steam-Electric Generating Plant
1000 Mwe
38% Thermal Efficiency
Fuel: 1% S, 11,770 Btu/lb.
Plant Area: 900-1200 acres
23.05 x 10^9 kwh/yr
Liquid Drainage
Te
Liquid Waste
497 Te suspended solid
66.2 Te organics
2.4 Te BOD
82.5 Te H2SO4
26.3 Te Cl2
41.7 Te phosphates
331 Te boron
2.4 Te chromates
Circulating
574,000


Delivered Electrical Energy 7.984 x 10^9 kwh
sion
10^9 kwh
Losses
Flue gas
9.69 x 10^11 cu ft
2.30 x 10^9 kwh waste heat
5.76 x 10^4 Te SO2
2.75 x 10^4 Te NOx
1506 Te CO
454 Te hydrocarbons
7.62 Te aldehydes
5.0 mCi Th230 Ra226
8.0 mCi Th228, 232 Ra228
Airborne particulates
Fly Ash Removal 99% Recovery
Flue Gas
Recovered Fly Ash
2.88 x 10^5 Te
461 mCi Th230 Ra226
778 mCi Th228, 232 Ra228
Bottom Ash and Fly Ash Storage 25 ft depth
Liquid
Liquid Drainage
17-25 acres
Bottom Ash
7.27 x 10^4 Te
116 mCi Th230 Ra226
196 mCi Th228, 232 Ra228
Drift
287 gal./min.
286 Te dissolved solids
Humidified Air
1.37 x 10^7 Te H2O evaporated
11.07 x 10^9 kwh waste heat
Evaporative Cooling Tower 6 acres
rculating Water
4,000 gal./min.
Blowdown Water
4290 gal./min.
4270 Te dissolved solids
Makeup Water
11,430 gal./min.

TEKNEKRON, INC.

Principal Investigator: [illegible]
Project Director: Dr. W.J. [illegible]
Research Associate: [illegible]

Using the estimate of 17.820 tons overburden removed per ton of coal mined[2], open pit mining of the required 3.04×10^6 Te of raw coal involves the removal of 5.05×10^7 Te of overburden. After removal of the coal, the major portion of the overburden is returned to the pit. The remaining overburden appears as wastes at the mine site in dumps, etc., at an estimated amount of 1.166 tons of overburden waste per ton of coal produced[2], corresponding to 4.5×10^6 Te/yr of dumped overburden wastes.

On the basis of 309 acres of land per 10^6 tons mined[3], 1139 acres of land are consumed yearly in strip mining to furnish the required amount of raw coal at the mine for the 1000 MW(e) power plant. An additional 10% of the mined land area is damaged by the construction of access and haulage roads[4]. This results in a total affected land area of 1673 acres for the production of a one year supply of coal. An unknown quantity of airborne dust and particulates is produced by stripping and mining operations.

According to measurements at a Kentucky strip mine[5], surface water runoff carries 1900 tons of suspended solids per year per square mile of disturbed area. Assuming that drainage and erosion occurs at this rate for a period of ten years after mining, a total suspended solids runoff of 59,700 Te is calculated for the mining of an annual coal supply. The calculated dissolved solids load for the strip mined area is 31,700 Te, using the value [illegible] tons per square mile[5] of affected area. This also assumes a 10 year drainage period subsequent to the disturbance of the land by strip mining.

Acid leaching and drainage of 100 lb. of acid per acre per day from mine site mineral waste piles has been reported(6). A typical waste pile contains about 50,000 tons per acre(6). From these data the annual acid drainage or runoff is 7.228 x 10^{-4} Te acid per Te of piled waste per year. The 4.6 x 10^{6} Te of overburden residue would yield a total of 33,200 Te acid wastes assuming a ten year drainage period. Quantitative estimates of acid drainage from strip mine dewatering operations during coal extraction were not available for the present study.

3.3 Underground Mining

The average coal-resource extraction efficiency for underground coal mining is 5/8(7). Thus, a resource of 6.08 x 10^{6} Te of coal/year is required in an underground mine to supply 3.80 x 10^{6} Te of raw coal/year at the mine mouth.

Water is used in underground mining at the rate of 11 gallons per ton of coal mined(8), which scales to 1.64 x 10^{5} Te/yr of water for the present flowsheet.

Following underground mining, land subsidence occurs on an average of 0.1 acres subsiding 3 to 5 feet per 500 tons of coal removed(9). This results in the eventual damage of 838 acres of land due to underground mining of one years supply of bituminous coal for a 1000 MW(e) power plant.

Solid wastes from underground coal mining are produced at the rate of 38.1 tons per 1000 tons of raw coal produced(7), which scales to 1.62 x 10^{5} Te/yr of the underground mining of solid wastes for the present flowsheet.

An estimated 6 x 10^6 tons of acid drainage from underground coal mining occurs annually in the U.S.(10) The coal required for a 1000 Mw(e) power plant represents 1.13% of the underground mined coal production in the U.S. in 1969*. This fraction of the total annual acid drainage is 48,400 te acid. Assuming that the drainage from a mine occurs for a period of 10 years, an estimated 484,000 te of acid can be attributed to the mining of a year's supply of coal for a 1000 Mw(e) power plant.

3.4 Raw Coal Cleaning

The calculations for the flowsheet are based on the assumption that all the coal produced, whether from underground or strip mining is mechanically cleaned at the mine site. Memmering(12) describes a modern mine-site coal cleaning facility which prepares coal for shipment to an electric utility. The cleaning process includes mechanical crushing and sizing, washing and gravity separation to remove inorganic impurities such as shale, clay and pyrites that are associated with coal deposits. Mechanical and thermal dewatering, or drying, techniques are generally used to remove the water accumulated by the coal in the cleaning process. Thermal and air drying are the major source of airborne particulates from coal cleaning operations.

On an industry wide basis, the materials extraction efficiency for coal cleaning is 77%**. Thus, of the 3.80 x 10^6 te of raw coal leaving the mine, 3.08 x 10^6 Tn of clean coal leaves the cleaning plant for shipment to the power plant.

---

*Calculated from data presented in Reference (11), p. 358.

**Calculated from data presented in Reference (11), p. 357.

An estimated 500-600 acres are required for a modern mine site coal cleaning facility[10]. This includes some area for mining equipment and coal cleaning waste storage (cf. Section 3.5).

For coal cleaning, 500 gallons of water are required per ton of coal processed, of which 18 gallons per ton are consumed or lost[8]. The water necessary to clean 3.96 x 10^6 Tn/yr of raw coal is 8.08 x 10^6 Tn/yr, of which 2.98 x 10^5 Tn/yr are used consumptively.

An estimate of the amount of solid wastes produced in coal cleaning can be obtained from the 75% materials extraction efficiency for coal cleaning. Neglecting the relatively small amounts of waste produced as airborne particulates and liquids, i.e., assuming that 25% of the input becomes solid wastes, an estimated 0.97 x 10^6 Tn/yr of solid wastes are produced.

Up to 1000 tons of black water (water containing 4 to 8% coal solids) per 500 tons of clean coal produced are generated[8]. This results in an estimated 6.07 x 10^6 Tn of black water produced in cleaning the coal.

Airborne particulate emissions from coal cleaning are estimated from an EPA emissions factor of 20 lb. particulates per ton of coal processed[11]. Assuming 99% particulate control, the release of [illegible] of airborne particulates are estimated for coal cleaning.

3.5 Coal Cleaning Waste Storage

Coal cleaning yields up to 0.97 x 10^6 Tn/yr of solid wastes including coal particles, rock and minerals. Cleaning wastes from strip mined coal can be returned to the pit for disposal, but wastes from underground mined coal are generally stored in surface piles.

Cleaning wastes are typically piled at 50,000 tons per acre[6]. The land requirement for storage of 9.07 x 10^5 Ta/yr of cleaning wastes is therefore 20 acres per year.

The suspended solids load in mine spoilbank runoff has been reported[6] as 27,000 tons per square mile per year. Assuming that the mine spoils are similar to coal cleaning refuse, and that the drainage occurs for 10 years, 7650 Ta/yr of suspended solids are attributable to coal cleaning waste drainage associated with the coal for a 1000 Mw(e) power plant.

Spoilbank runoff carries a dissolved solids load of 14,000 tons per square mile per year[6], which leads to an estimate of 3970 Ta/yr of dissolved solids in runoff from coal cleaning wastes (assuming a 10 year drainage period).

On the basis of 100 lbs. acid per acre per day[6] for acid drainage from refuse piles at coal mine sites, the 20 acre refuse pile yields 3300 Ta/yr acid for an assumed 10 year drainage period.

An unknown quantity of airborne particulates are produced from wind suspension of mine-site coal-waste piles and from burning waste piles[6].

5.6 Rail Transport to Power Plant

It is assumed that the yearly fuel requirement of 3.08 x 10^6 Ta of cleaned coal is shipped to the power plant by rail. The average length of coal haul by rail in the U.S. is 300 miles[14]. Assuming an average width of 100 ft. for rail right-of-way, 300 miles of rail require 3,640 acres of land.

An estimated 0.1% of the total tonnage shipped by rail is lost by spillage in loading, unloading and transit[9], leading to an estimated shipping loss of 3,040 te/yr of coal.

An unknown quantity of airborne particulates, in the form of coal fines or dust, is released in the handling and shipment of coal by rail. Emissions from locomotives are not considered.

3.7 Coal Storage at Power Plant

An on-site coal storage capacity for 90 days of power plant operation is assumed[15], corresponding to about 60 acres piled to a depth of 40 feet[15] for a 1000 MW(e) power plant. An unknown quantity of liquid waste consisting of water runoff containing dissolved and suspended coal particles will be produced from the coal storage piles, and an unknown quantity of coal fines will become airborne by wind. In cold climates, the spraying of coal with oil or saline solution to prevent freezing during transportation will add to liquid wastes from storage pile drainage.

3.8 Power Plant Operation

Energy consumption for a typical 1000 MW(e) coal fired power plant is shown in Table 3.1. Based upon an overall thermal efficiency of 38% and a fuel heating value of 11,700 Btu/lb., the annual fuel consumption at 100% load factor is 3.03 million tonnes of coal.

Table 3.1

Thermal Energy Balance for Coal-Fired Power Plant - 1000 MW(e)

	Percent of Thermal Input[10]	Energy at 100% load Factor, kWh/yr
Net electrical output	38	8.76×10^9
Heat rejected to condenser	48	11.07×10^9
Sensible heat in flue gas	10	2.30×10^9
Internal thermal losses and plant consumption	4	0.92×10^9

The coal is assumed to contain 1% sulfur, typical of the low-sulfur coal in demand for power plant fuel. The ash content of bituminous coal ranges from 1% to 30%[10], and a typical value of 12% is used in the present study. It is assumed that 80% of the ash appears as suspended particles of fly ash in the flue gas leaving the boiler, and the remaining 20% appears as furnace bottom ash, for typical pulverized coal fired units[10].

3.2 Flue Gas Effluents

Flue gas is discharged at the rate of 5.00×10^{11} cu.ft./yr, carrying the chemical effluents listed in Table 3.2.

Table 3.8

Gaseous Effluents from Coal Fired Power Plant - 1000 MW(e)

	Emission Factor[16] lb/ton coal burned	Effluents Te/yr
Sulfur oxides (for 1% sulfur coal)	38	5.76×10^4
CO	1	1516
Nitrogen oxides	18	2.73×10^4
Hydrocarbons	0.3	454
Aldehydes	0.005	7.57

The discharged flue gas also contains 2910 Te/yr of fly ash and associated radioactivity, as discussed in Section 3.10.

3.10 Fly Ash Removal

It is assumed that electrostatic precipitators remove 99% of the fly ash in the flue gas, which is representative of requirements for new power plants.[17] One percent of the entering particulates, or 2910 Te/yr of fly ash particulates, are emitted from the stack. The stack gas cleaning system will yield 2.88×10^5 Te/yr of fly ash residue from the fly ash entering the flue gas. Fly ash removal systems generally carry the particulates out in liquid slurries, but ultimately the residue nearly all ends up in solid form, as is indicated in the flowsheet.

Modern power plant bottom ash and fly ash handling systems use water as a carrier with a major portion of the water being reused. An unknown quantity of liquid wastes are generated by fly ash precipitate handling systems.

An analysis of radioactivity in coal ash reveals the concentrations in picocuries per gram of ash, as shown in Table 3.3. The thorium-decay daughters Ra^{228} and Th^{228} are assumed to be in secular equilibrium with Th^{232} in the ash, and secular equilibrium of the uranium-decay daughters, Th^{230} and Ra^{226} is assumed. It is assumed that these radionuclides form stable oxides upon combustion and are carried by the ash, i.e. the radioactivity per unit of ash remains constant. The 2010 Te of ash emitted from the stack contains the radionuclides shown in Table 3.3.

Table 3.3

Radium and Thorium Radionuclides Released from Coal-Fired Power Plant Stack - 1000 MW(e)

	Content in Coal Ash(21) picocuries/gm ash*	Quantities released with discharged fly ash curies/yr
Th^{230}, Ra^{226}	1.8	0.0046
Th^{232}, Ra^{228}, Th^{228}	2.1	0.0019

---

*One picocurie = 10^{-12} curie

3.11 Ash Storage

A total of 3.60×10^{5} Te of ash is added to on-site storage each year. A 1000 MW(e) power plant operating for 35 years at 60% average load factor requires 80 to 400 acres for ash storage if piled to an average depth of 25 feet(16). Scaling to a 1000 MW(e) plant at 100% load factor yields a land requirement for ash storage of 17 to 23 acres per year.

An unknown quantity of liquid wastes are produced from surface runoff, and an unknown quantity of ash dust is produced from the ash storage piles.

Based on the ash analysis presented in Table 3.3, the annual quantities of radioactive radium and thorium in the stored ash are shown in Table 3.4.

Table 3.4

Radium and Thorium Radionuclides in Stored Ash - 1000 MW(e)

	Ra^{226}, Rn^{222} curies/yr	Th^{232}, Ra^{228}, Th^{228} curies/yr
Bottom ash	0.116	0.186
Precipitated fly ash	0.461	0.730
Total in stored ash	0.577	0.916

3.12 Liquid Wastes

Liquid wastes from a power plant are primarily due to boiler blowdown which contains chemicals added for corrosion and organic growth control. The emission rates for the various pollutants in liquid wastes and the calculated releases for a 1000 MW(e) power plant are listed in Table 3.5.

Table 3.5

Boiler Blowdown Releases in Liquid Wastes - 1000 MW(e)

Component	Releases[19] lb/day	Releases Te/yr
Suspended solids	3,000	497
Non-degradable organics	400	66.2
BOD	15	2.4
Acids	500	82.8
Alkalinity	65	10.8
Chlorine	180	29.8
Phosphates	250	41.7
Boron	2,000	331
Chromates	15	2.4

3.11 Condenser Cooling

It is assumed that the condenser cooling for the 1000 MW(e) coal fired power plant is provided entirely by evaporative cooling towers. The characteristics of the towers are scaled on the basis of the amount of heat rejected by the condenser, from the parameters presented in Section 6.2 and are summarized in Table 3.6. Additional environmental effluents associated with cooling tower operation are discussed in Section 6.2.

Table 3.8

Cooling Tower Quantities for Coal-Fired Power Plant - 1000 MW(e)

Thermal load	11.07 x 10^9 kwh/yr
Circulating coolant	576,000 gal/min
Blowdown discharge rate	4280 gal/min
Dissolved solids released in blowdown	4270 Te/yr
Make-up water rate	11,630 gal/min
Drift rate	287 gal/min
Dissolved solids released in drift	288 Te/yr
Evaporated water	1.37 x 10^7 Te/yr

The land area required is scaled from data presented by Farber and Krenkel[22] for natural draft towers and is about 6 acres.

REFERENCES

1. Averitt, P., "Stripping Coal Resources in the U.S. - January 1, 1970," U.S. Geological Survey Bulletin 1322, Washington, D.C.

2. United States Department of Interior, "Environmental Effects of Underground Mining and Processing."

3. Stahl, R. C., "Issues Related to Surface Mining," A report of the Senate Committee on Interior and Insular Affairs, Washington, D.C. (1971).

4. United States Department of Interior, "Surface Mining and Our Environment," Washington, D.C., p. 52 (1971).

5. United States Department of Interior, "Influences of Strip Mining on the Hydrologic Environment of Parts of Beaver Creek Basin, Kentucky, 1955-66," Geological Survey Paper 427-C, p. C-2 (1970).

6. United States Environmental Protection Agency, "Control of Mine Drainage from Coal Mine Mineral Wastes," 14010 DDH (August, 1971).

7. Averitt, P., "Coal Resources of the U.S., January, 1967," U.S. Geological Survey Bulletin No. 1275, Washington, D.C., p. 29 (1969).

8. United States Department of Interior, "Water Use in the Mineral Industry," Bureau of Mines Information Circular 8285, p. 36 (1966).

9. Delson, J. K. and R. J. Frankel, "Residuals Management in the Coal-Energy Industry," p. II-26.

10. Fortune, M., "Environmental Consequences of Extracting Coal: Underground Mining," Electric Power and Human Welfare, AAAS/CEA group preliminary report August (August, 1972).

11. United States Department of Interior, "Minerals Yearbook - 1969," vols. I-II.

12. Remering, L. R., "Coarse Coal Cleaning at Monterey No. 1 Preparation Plant," Mining Congress Journal, 58:3, pp. 43-48 (March, 1972).

13. United States Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors" (February, 1972).

14. National Coal Association, "Bituminous Coal Facts - 1970," Washington, D.C. (1970).

15. "Considerations Affecting Steam Power Plant Site Selection," Energy Policy Staff, Office of Science and Technology (December, 1968).

16. Cuffe, S. T. and R. W. Gerstle, "Emissions from Coal-Fired Power Plants: A Comprehensive Summary," U.S. Dept. of HEW, PHS Pub. No. 999-AP-35 (1967).

17. "Fly Ash/Sulfur Removal Systems are Slated for Two Plants," Electrical World, 176, 33 (September 1, 1971).

18. Eliassen, R., "Power Generation and the Environment," Bulletin of the Atomic Scientists 27:7 (September, 1971).

19. Bysinger, G. and W. D. Jackson, "Industrial Waste Studies: Steam Generating Plants," Environmental Protection Agency.

20. Esso Research and Engineering Co., "Systems Study of NOx Control Methods for Stationary Sources, Final Report," vol. II Report GR-2-NOS-69.

21. Martin, J. E., E. D. Harward, D. T. Oakley, "Comparison of Radioactivity from Fossil Fuel and Nuclear Power Plants," in Environmental Effects of Producing Electric Power, JCAE Hearings 91st Congress, 1969, Part 1, p. 773.

22. Parker, F. L. and P. A. Krenkel, "Engineering Aspects of Thermal Pollution," Vanderbilt University Press, 351 (1969).

4. ELECTRICAL POWER FROM RESIDUAL FUEL OIL

4.1 Introduction

The fuel cycle for a 1000 Mw(e) power plant fueled with residual oil derived from domestic crude is shown in Figure 4.1. The maximum domestic environmental effects are associated with oil produced, processed and consumed within the U.S., and therefore other fuel sources for power plants, such as imported residual fuel oil, will not be considered here.

The flowsheet quantities for fuel cycle operation prior to the power plant are developed primarily on the basis of industry-wide data, scaled to the oil flow associated with the annual fuel supply for a 1000 Mw(e) power plant.

Residual fuel oil is a by-product of the domestic petroleum industry. The flowsheet illustrates the operations of crude production, transport, and the refining of crude into typical refinery products and residual crude by-products. Alternate production of domestic crude oil from continental oil fields and from off-shore fields is illustrated.

The material and environmental quantities are those resulting from the production of the required amount of residual fuel oil to fuel an oil-fired 1000 Mw(e) power plant for one year at 100% load factor. The environmental effluents associated with production, transportation, and refining are, therefore, only partly attributable to producing power-plant fuel.

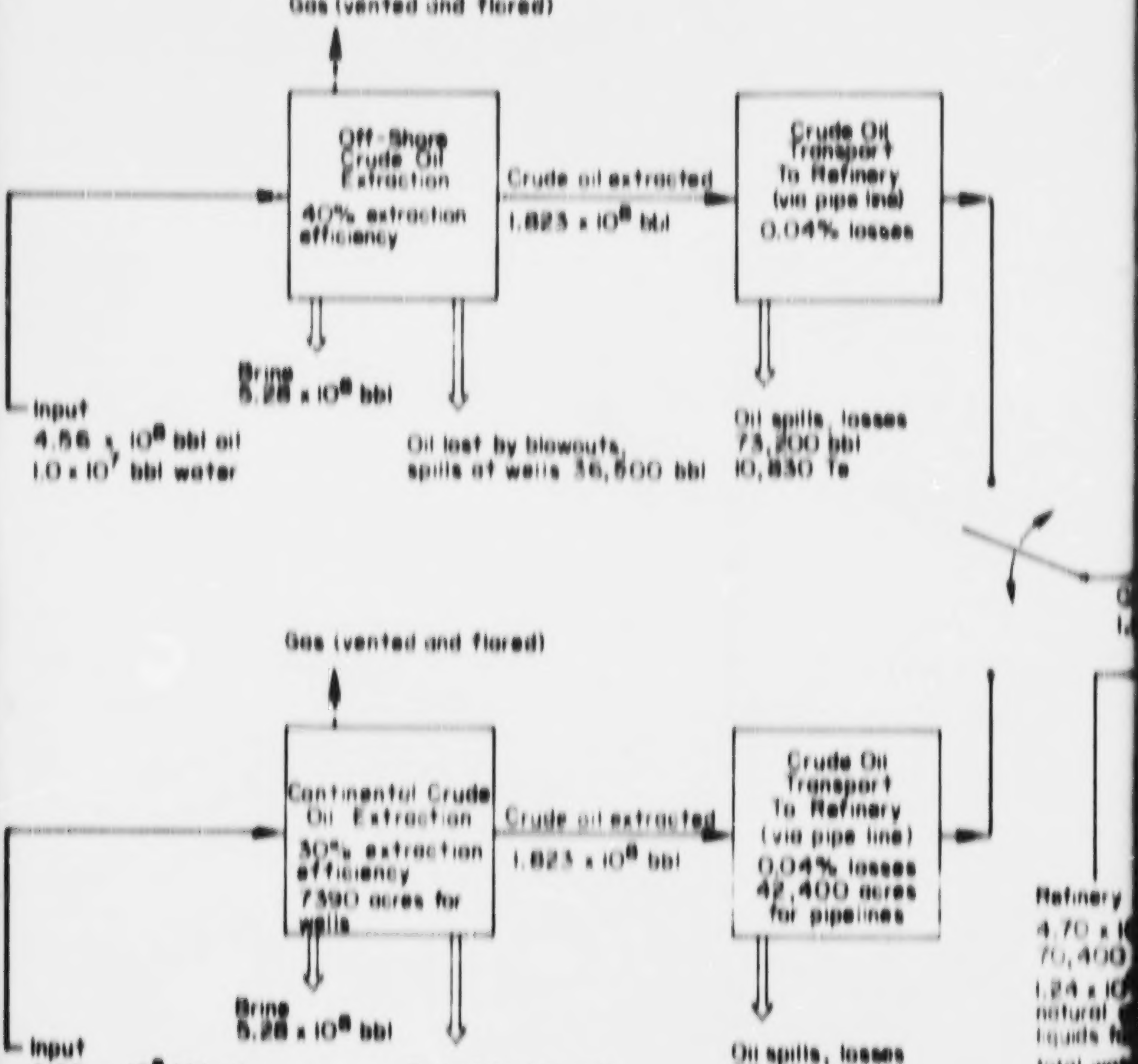
FLOW QUANTITIES ARE STATED IN METRIC TONNES / YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

〰〰〰➤ ELECTRICAL ENERGY
- - - - - - ➤ AIRBORNE RELEASE
⇨ LIQUID EFFLUENT
➡ SOLID EFFLUENT

To = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE
CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

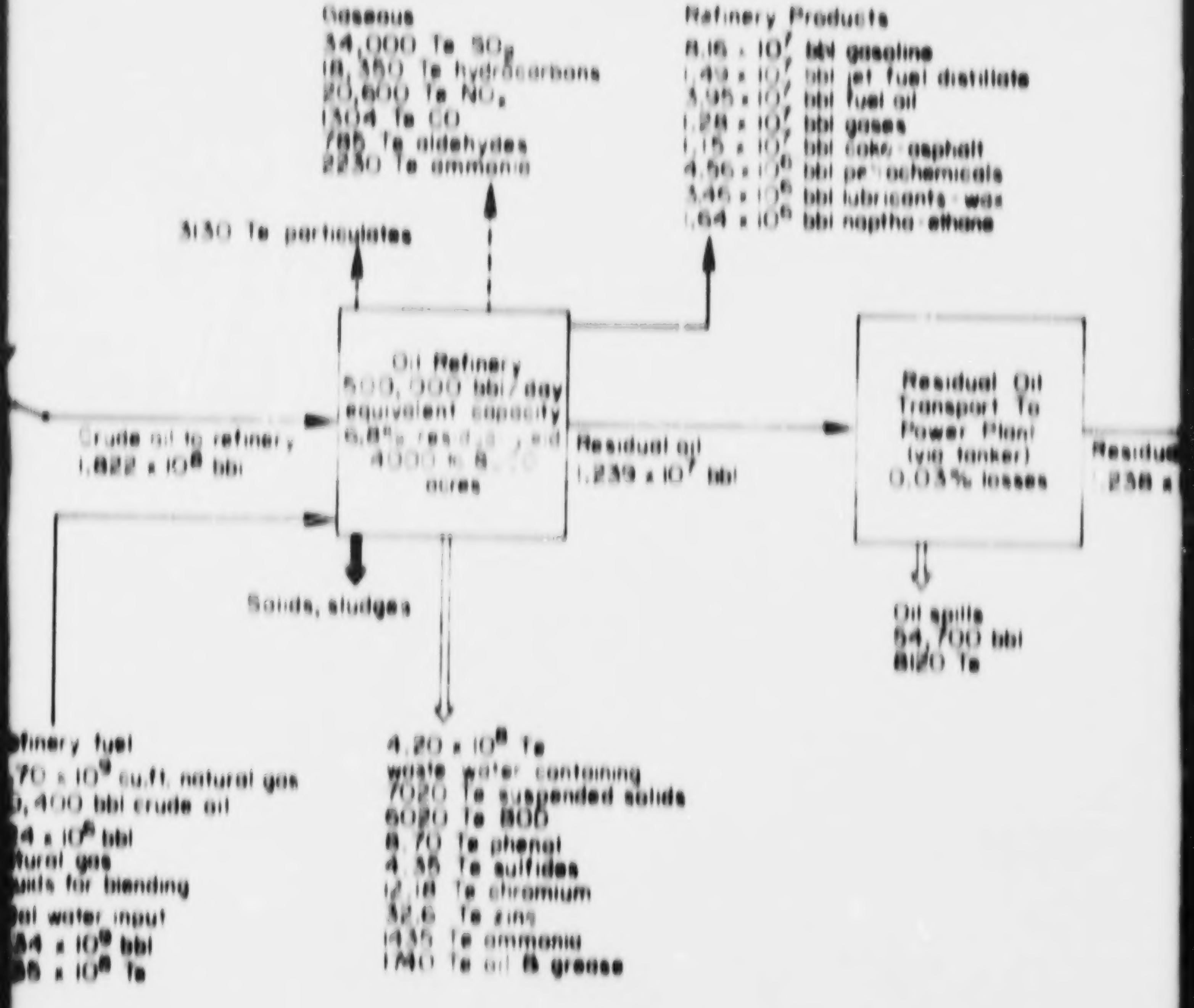
TEKNEKRON, INC.
BERKELEY, CALIFORNIA



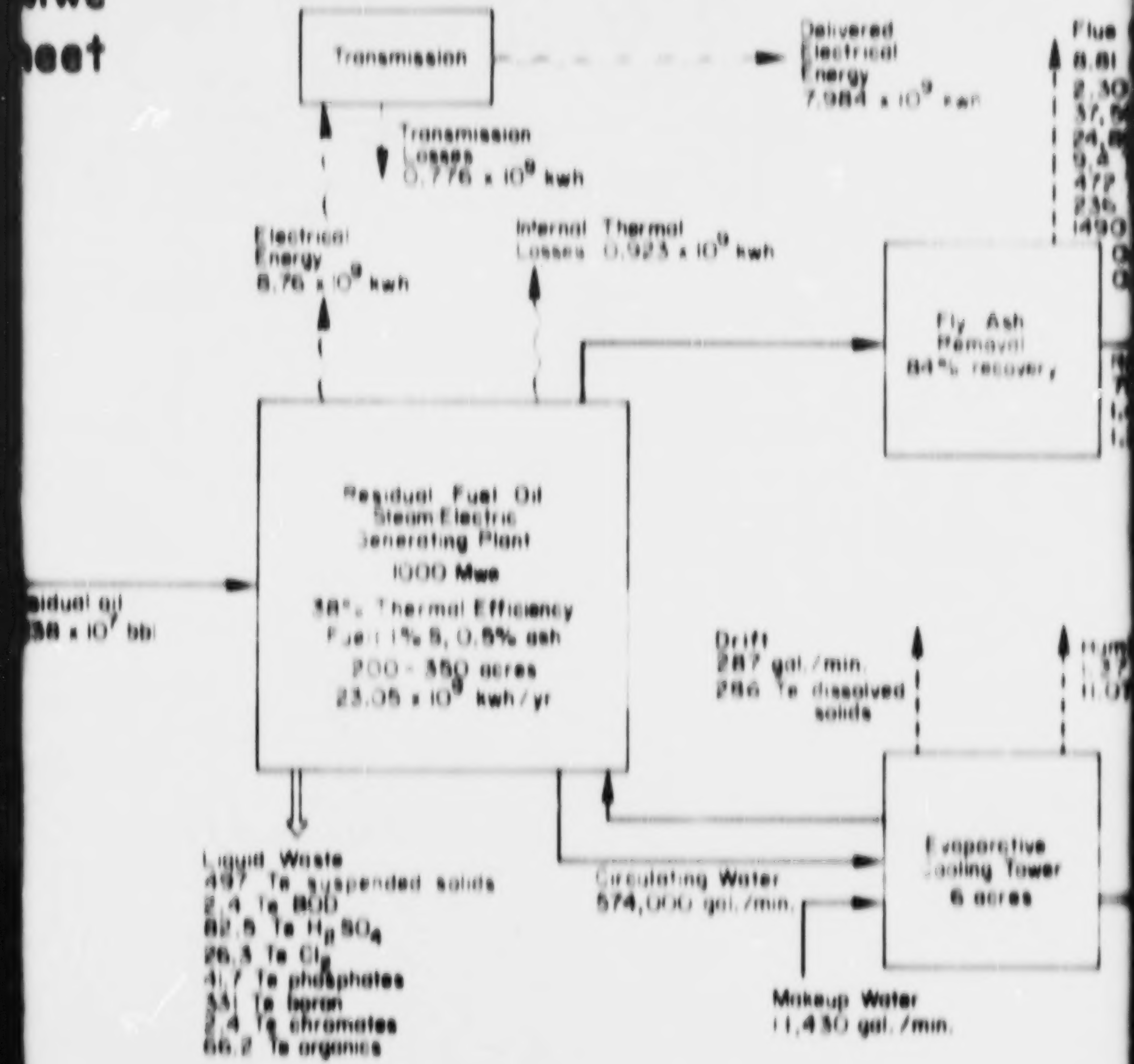
Gas (vented and flared)
Off-Shore Crude Oil Extraction
40% extraction efficiency
Crude oil extracted
1.823 x 10⁸ bbl
Crude Oil Transport To Refinery (via pipe line)
0.04% losses
Brine 5.28 x 10⁸ bbl
Input
4.56 x 10⁸ bbl oil
1.0 x 10⁷ bbl water
Oil lost by blowouts, spills at wells 36,500 bbl
Oil spills, losses
73,200 bbl
10,830 Te
Gas (vented and flared)
Continental Crude Oil Extraction
30% extraction efficiency
7390 acres for wells
Crude oil extracted
1.823 x 10⁸ bbl
Crude Oil Transport To Refinery (via pipe line)
0.04% losses
42,400 acres for pipelines
Brine 5.28 x 10⁸ bbl
Input
6.08 x 10⁸ bbl oil
1.0 x 10⁷ bbl water
Oil lost by blowouts, spills at wells 20,000 bbl
Oil spills, losses
73,200 bbl
10,830 Te
Refinery
4.70 x 1
70,400
1.24 x 10
natural
liquids f
total wa
3.34 x
5.35 x

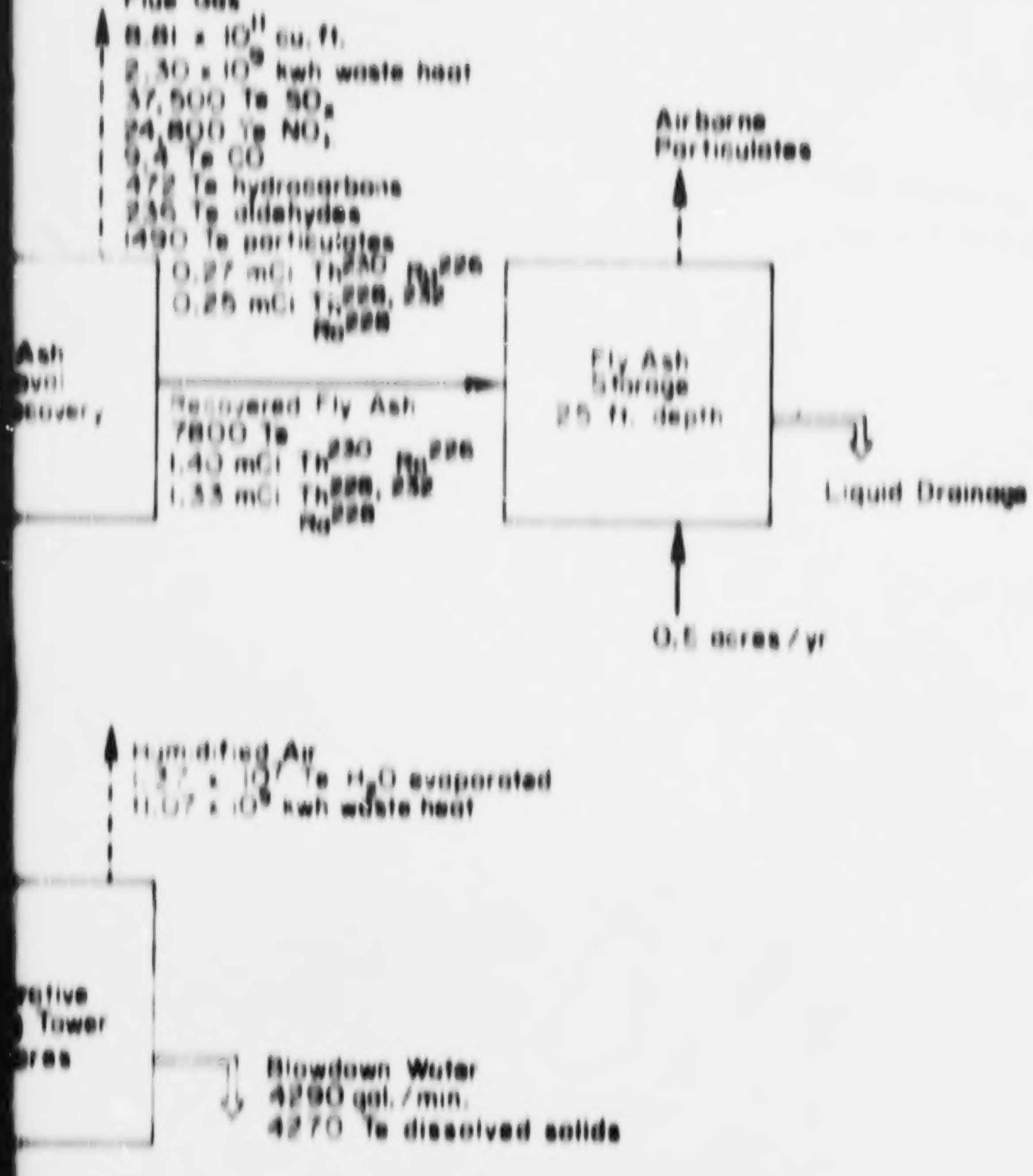
Figure 4.1

Residual Fuel Oil Power Plant 1000 Mw
Material And Environmental Release Flowshee


Gaseous
34,000 Te SO_2
18,350 Te hydrocarbons
20,600 Te NO_x
1304 Te CO
785 Te aldehydes
2230 Te ammonia
3130 Te particulates
Refinery Products
8.16 x 10^7 bbl gasoline
1.49 x 10^7 bbl jet fuel distillate
3.95 x 10^7 bbl fuel oil
1.28 x 10^7 bbl gases
1.15 x 10^7 bbl coke asphalt
4.56 x 10^6 bbl petrochemicals
3.45 x 10^6 bbl lubricants wax
1.64 x 10^6 bbl naptha ethane
Oil Refinery
500,000 bbl/day
equivalent capacity
6.8% residual oil
4000 to 8,70
acres
Crude oil to refinery
1.822 x 10^8 bbl
Residual oil
1.239 x 10^7 bbl
Residual Oil
Transport To
Power Plant
(via tanker)
0.03% losses
Residu
.238 x
Solids, sludges
Oil spills
54,700 bbl
8120 Te
finery fuel
70 x 10^9 cu.ft. natural gas
0,400 bbl crude oil
24 x 10^6 bbl
tural gas
uids for blending
tal water input
54 x 10^9 bbl
35 x 10^8 Te
4.20 x 10^8 Te
waste water containing
7020 Te suspended solids
6020 Te BOD
8.70 Te phenol
4.55 Te sulfides
12.18 Te chromium
32.6 Te zinc
1435 Te ammonia
1740 Te oil & grease

Mwe
heet


Transmission
Delivered Electrical Energy 7.984 x 10^9 kwh
Transmission Losses 0.776 x 10^9 kwh
Electrical Energy 8.76 x 10^9 kwh
Internal Thermal Losses 0.923 x 10^9 kwh
Flue
8.81
2,30
37,5
24,6
9.4
477
236
1490
Fly Ash Removal 84% recovery
Residual Fuel Oil Steam-Electric Generating Plant
1000 Mwe
38% Thermal Efficiency
Fuel: 1% S, 0.5% ash
200 - 350 acres
23.05 x 10^9 kwh/yr
sidual oil
38 x 10^7 bbl
Drift
287 gal./min.
286 Te dissolved solids
Evaporative Cooling Tower
6 acres
Circulating Water
574,000 gal./min.
Makeup Water
11,430 gal./min.
Liquid Waste
497 Te suspended solids
2.4 Te BOD
82.5 Te H_2SO_4
26.3 Te Cl_2
41.7 Te phosphates
331 Te boron
2.4 Te chromates
66.2 Te organics


Flue Gas
8.81×10^{11} cu. ft.
2.30×10^{9} kwh waste heat
37,500 Te SO_x
24,800 Te NO_x
9.4 Te CO
472 Te hydrocarbons
236 Te aldehydes
1490 Te particulates
0.27 mCi Th^{230}, Ra^{226}
0.25 mCi $Th^{228, 232}$, Ra^{228}
Ash
ovil
covery
Recovered Fly Ash
7800 Te
1.40 mCi Th^{230}, Ra^{226}
1.33 mCi $Th^{228, 232}$, Ra^{228}
Airborne
Particulates
Fly Ash
Storage
25 ft. depth
Liquid Drainage
0.6 acres/yr
Humidified Air
1.27×10^{7} Te H_2O evaporated
11.07×10^{9} kwh waste heat
rative
Tower
cres
Blowdown Water
4290 gal./min.
4270 Te dissolved solids

TEKNEKRON, INC.

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

4.2 Crude Oil Production

A yearly production of 1.023 x 10^8 barrels of crude oil at the well is required to produce sufficient residual fuel oil for the 1000 Mw(e) power plant. Production of this amount from off-shore wells would result in a yearly consumption of oil pool resource of 4.09 x 10^8 bbl, based on an extraction efficiency of 25%[1]. The estimated oil extraction efficiency for on-shore or continental oil wells is 60%[1], which results in a yearly consumption of 6.00 x 10^7 bbl of continental resource.

On the basis of data presented by Battermore[2], approximately 1 x 10^7 bbl/yr of water is required for the indicated yearly production of crude oil. Brine, or saline water, is present in underground oil pools and must be separated from the crude oil at the well site. The residue, containing small amounts of oil, must be disposed of as liquid waste. Based on 7.0 bbl of brine produced per barrel of crude oil[3], 6.00 x 10^8 bbl/yr of brine is produced.

An estimate of the number of wells required to produce the crude oil is obtained as follows. The average yearly production per well in the U.S. for the year 1969 was 3650 bbl*, which scales to 28,000 such average wells required to produce 1.023 x 10^8 bbl/yr of crude oil. Assuming one quarter acre of land per continental well**, 7,000 acres are required for the annual production shown on this flowsheet.

---

*Calculated from data presented in Reference (3), p. 604-05.

**An estimate for the purposes of this report, including land used for oil field water separators and oil gathering mains, etc.

Roughly 0.02% of the oil produced from off-shore wells is lost at the well site by spills and blowouts[4]. This results in 38,500 bbl/yr of oil waste at the off-shore well sites. On the basis of 0.01% losses by spills, blowouts and incomplete separation from waste water for continental production[4], we estimate 20,000 bbl of oil wastes at the wells associated with the production quantities shown on the flowsheet. An unknown quantity of natural gas associated with oil bearing formations is vented and flared at the wells.

4.3 Transport from Wells to Refinery

The material quantities for on-shore oil transport are identical with those developed for off-shore wells, with the exception of the land area required for oil pipeline right-of-way. On an industry wide basis, an estimated 0.04% of oil transported from wells to refineries via pipeline is lost due to leaks and spills[4]; this results in a loss of approximately 73,200 bbl/yr for the transported quantities shown on the flowsheet.

In 1969 there were 46,000 miles of oil-gathering pipelines[5]. The crude oil production associated with a one year supply of residual fuel oil for the 1000 Mw(e) power plant represents 6.58% of the domestic crude oil production for 1969*. This share of the total U.S. oil-gathering pipeline mileage and an assumed 14 acres of land required per mile of pipeline, yield a land requirement of 42,400 acres. Other environmental effects associated with pipeline construction are not included in this report.

---

*Calculated from data represented in Reference (3), p. 830.

4.4 Oil Refining

As calculated from data reported for 1969 in the Minerals Yearbook[3], the residual fuel oil output of domestic oil refineries was 6.8% of the crude oil input. On this basis, refinery capacity of 500,000 bbl/day is required to supply the annual residual fuel oil to a 1000 Mw(e) power plant.

The hypothetical refinery discussed in this report is based on industry-wide data, representing contributions from the mix of existing refinery operations in the U.S. It does not represent the most modern available technology and does not necessarily represent the operation of any particular refinery. However, some of the effluent data are based on data from individual facilities when these are the only sources available.

One refinery of 100,000 bbl/day capacity requires 1400 acres of land[6], which scales to 7,000 acres for a 500,000 bbl/day refinery. Another refinery of 600,000 bbl/day capacity occupies 5000 acres[14], which scales to 4,170 acres for 500,000 bbl/day. We have used 4000 to 8000 acres as the range of land area for the 500,000 bbl/day refinery projected in the present study.

The model refinery shown here requires the input of additional quantities of crude oil and natural gas for refinery fuel. Other significant material inputs include natural gas liquids, used as blending stock for the manufacture of various refinery products, and water. In 1969, for the industry as a whole, 0.03975 of the refinery crude oil input was used as refinery fuel as calculated from data in the 1969 Minerals Yearbook[3]. Scaling to the flowsheet refinery input yields 70,440 bbl/yr of crude oil for refinery fuel for the present flowsheet. A similar procedure using natural gas use data(3) results in the estimate of 4.70×10^9 cu.ft./yr of natural gas as fuel for the model refinery. U.S. refineries used 2.65×10^8 bbl of natural gas liquids for blending and as feed stock in various manufacturing processes in 1969(3). On a pro-rata basis, the 500,000 bbl/day refinery would utilize 1.24×10^6 bbl/yr of natural gas liquids.

An estimated 770 gal of water per barrel of crude oil input is required in a typical refinery(7), which corresponds to a yearly consumption of 1.4×10^{11} gal for the 500,000 bbl/day refinery. The fraction of water reused varies considerably in the industry.

The yields of important refinery products other than residual fuel are shown in Table 4.1.

Table 6.1

Refinery Products

Item	Yield in percent of crude input(1)	Annual yields for 500,000 bbl/day refinery bbl/yr
Gasoline	44.7	8.16×10^7
Jet fuel	8.2	1.49×10^7
Distillate fuel oil	21.7	3.96×10^7
Gases	7.0	1.28×10^7
Naptha-ethane	0.9	1.64×10^6
Petrochemicals	2.5	4.56×10^6
Lubricants-wax	1.9	3.46×10^6
Coke, asphalt, road oil	6.3	1.15×10^7
Residual fuel oil	6.8	1.239×10^7
	100.0%	

Due to the lack of industry-wide data on refinery effluents, the environmental release quantities calculated for the model 500,000 bbl/day refinery are derived in part from reported limits for a particular installation and in part from emission factors. An estimated 3.6 tons/day of particulates are emitted from a 100,000 bbl/day refinery(6). Scaling to the 500,000 bbl/day refinery yields 3130 Te of particulates per year. The emission rates of gaseous effluents are given in Table 4.2.

Table 4.2

Oil Refinery Gaseous Effluents

Item	Emissions from 100,000 bbl/day refinery(6) tons/day	Yearly emissions from 500,000 bbl/day refinery Te/yr
SO_2	39.1	34,000
Hydrocarbons	21.1	18,350
NO_x	23.7	20,600
CO	1.5	1,304

An estimated 50% of refinery input goes through fluidized-bed catalytic crackers which emit ammonia and aldehydes(7) at average rates(6) of 0.054 lb. of ammonia and 0.019 lb. of aldehyde per barrel of catalytic feed. This corresponds to 786 Te/yr of aldehydes and 2230 Te/yr of ammonia for the model refinery.

The quantities of liquid effluents are scaled from daily release limits reported for a 100,000 bbl/day refinery, and are shown in Table 4.3.

Table 4.3

Oil Refinery Liquid Effluents

Item	Daily effluents from 100,000 bbl/day refinery(9)	Yearly effluents from 600,000 bbl/day refinery Tm/yr
Total waste water	115 x 10^6 gal	4.70 x 10^8
Phenol	20 lb.	8.69
Sulfide	10 lb.	4.35
Chromium	28 lb.	12.18
Zinc	75 lb.	32.62
Ammonia	3300 lb.	1435
Oil and grease	4000 lb.	1740

Derived annual quantities of BOD and suspended solids are shown in Table 4.4.

Table 4.4

BOD and Suspended Solids in Oil Refinery Liquid Effluents

Item	Emission factors(10) lb/10^3 bbl crude input	Yearly effluents from 600,000 bbl/day refinery Tm/yr
BOD	73	6025
Suspended solids	85	7023

4.5 Transport of Residual Fuel Oil

Nearly all residual fuel oil from U.S. refineries is shipped by tanker or oil barge to power plants. For the purposes of this report, other modes of transport will not be considered. An estimated 0.03% of the oil shipped via tankers from refineries is lost by spills in loading and transport(4), corresponding to an annual spillage loss of 8,100 Te (54,700 bbl) for the present flowsheet. Fuel oil consumption as tanker fuel is not considered.

4.6 Power Plant Operation

The 1000 Mw(e) power plant is assumed to have an overall thermal efficiency of 38% and a 100% load factor. The overall energy budget is assumed to be the same as for the coal-fired plant (cf. Table 3.1). The thermal energy available from combustion of residual fuel oil used as the basis for calculations in this report is 6.36 x 10^6 Btu/bbl(8). Low-sulfur residual fuel oil containing 1% sulfur(11) is assumed, with an ash content of 0.05%(12). An estimated 200-300 acres of land are required for a 1000 Mw(e) oil fired power plant(13); this is considerably less than that required for a coal-fired plant because of less storage area for ash and fuel.

Liquid wastes associated with boiler feedwater treatment and blowdown are also assumed to be identical to those for the coal-fired power plant, summarized in Table 3.6.

4.7 Flue Gas Effluents

On the basis of 215 cu. ft. of flue gas per pound of residual fuel oil burned(11), the annual quantity of flue gas produced by the 1000 MW(e) power plant is 8.81 x 10^{11} cu. ft. Assuming that all of the ash appears as fly ash upon combustion, 8800 Te of fly ash is released annually to the flue gas system. A fly-ash removal efficiency of 84% for an oil-fired power plant is assumed(12), resulting in an annual particulate release to the environment of 1400 Te.

The yearly quantities of gaseous effluents are given in Table 4.6.

Table 4.6

Gaseous Effluents from Oil Fired Power Plant - 1000 MW(e)

Pollutant	Emission Factors lb/10^3 gal oil consumed(8)	Yearly emissions Te/yr
SO_x	157 (for 1% sulfur oil)	37,000
CO	0.04	9.4
Hydrocarbons	2	472
NO_x	105	24,770
Aldehydes	1	236

Radium and thorium radionuclides exist in residual fuel oil ash in measurable quantities(12). Concentrations reported for these radionuclides in oil ash, corrected by the assumption that Ra^{226} is in secular equilibrium with Th^{230} and that Th^{232}, Ra^{228} and Th^{228} are also in secular equilibrium, are listed in Table 4.6

Table 4.6

Radium and Thorium Radionuclides in Residual Fuel Oil Ash

	Th^{230}, Ra^{226}	Th^{232}, Ra^{228}, Th^{228}
Concentration in oil ash(12)	0.16 picocuries*/gm dry ash	0.17 picocuries*/gm dry ash
Total amount in annual fuel supply for 1000 Mw(e) power plant	1.67 millicuries/yr	1.68 millicuries/yr
Annual releases from power plant stack	0.27 millicuries/yr	0.29 millicuries/yr
Annual quantity collected in fly ash precipitate	1.40 millicuries/yr	1.39 millicuries/yr

---

*Picocurie = 10^{-12} curies

4.8 *Fly Ash Storage*

Of the 8000 Tn of fly ash produced annually in the power plant, approximately 7920 Tn is recovered in the gas cleaning system and must be stored at the power plant site or disposed of in some other fashion. An estimated annual land area requirement for dry surface pile storage can be made by scaling from the approximately 20 acres/yr required for the annual production of 800,000 Tn of ash by the coal-fired power plant. This results in an annual land requirement of about 0.5 acres. If landfill methods of storage or disposal were used, considerably more land area would be necessary, but alternate use of the land would be possible after the filling operations were completed. If uncovered surface storage is used, an undetermined quantity of airborne particulates will be produced by wind action. Liquid wastes are produced by the use of water slurries to transport fly ash from stack cleaning to storage sites. Additional, but unknown quantities are produced by drainage from stored piles and land fill sites.

4.0 Condenser Cooling

Condenser cooling for the 1000 Mw(e) residual-oil-fired power plant is assumed to be provided entirely by evaporative cooling towers. The cooling tower quantities are calculated by scaling from the parameters developed in Section 6.2 on the basis of heat rejected by the condenser. The quantities, are identical to those for the 1000 Mw(e) bituminous coal power plant summarized in Section 6.2.

REFERENCES

1. National Petroleum Council, "An Initial Appraisal by the Oil Supply Task Group 1971-1985," Washington, D.C., p. 46 (1972).

2. [illegible], P. H., "Water Use in the Petroleum and Natural Gas Industries," Washington, D.C., p. 38 (1966).

3. United States Department of Interior, "Minerals Yearbook - 1969," vols. I-II.

4. United States Department of Interior, "Draft Environmental Statement for Proposed Outer Continental Shelf Oil and Gas General Lease Sale - Off-Shore Eastern Louisiana," Washington, D.C. (1972).

5. "American Almanac for 1972," p. 670.

6. Stanford Air Pollution Workshop, Final Report, "Air Pollution in the San Francisco Bay Area," p. 75 (1970).

7. Nemerow, N. L., "Liquid Waste of Industry: Theories, Practices and Treatment," Addison-Wesley, p. 466 (1971).

8. United States Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors," p. 1-16 (1972).

9. San Francisco Bay Area Water Conservation District limits reported for a 150,000 bbl/day refinery in, "San Francisco Chronicle," September 27, 1972.

10. American Petroleum Institute, Committee for Air and Water Conservation, "1967 Domestic Refinery Effluent Profile," Washington, D.C. (September, 1968).

11. Smith, W. S., "Atmospheric Emissions from Fuel Oil Combustion," U.S. Public Health Service, Environmental Health Series, Air Pollution No. 999-AP-2, p. 8 (1962).

12. Martin, J. E., E. D. Harward, D. T. Oakley, "Comparison of Radioactivity from Fossil Fuel and Nuclear Power Plants," Department of Health, Education and Welfare, p. 8 (November, 1969).

13. Office of Science and Technology, Energy Policy Staff, "Considerations Affecting Steam Power Plant Site Selection," p. 11 (December, 1968).

14. Williams, R. H., Private Communication (The Energy Policy Project) (January 1973).

6. ELECTRICAL POWER FROM NATURAL GAS

6.1 Introduction

The fuel cycle flowsheet shown in Figure 6.1 for a 1000 Mw(e) power plant is based upon processed natural gas produced from continental domestic wells. Other supply schemes such as imported gas or gas from oil-producing wells are also used by various electrical generating plants but are not considered here. The flowsheet quantities for production, processing, and transport of natural gas fuel are developed primarily on the basis of industry-wide data, scaled to the gas volume required for a 1000 Mw(e) power plant.

6.2 Gas Production

A yearly production of 9.04 × 10^{10} cu. ft. of natural gas is required to furnish the annual fuel supply for the 1000 Mw(e) power plant. Assuming an 80% extraction efficiency for gas wells*, the annual consumption of gas-field resource is 1.17 × 10^{11} cu. ft.

In 1969, there were about 114,600 gas wells in production in the U.S. producing some 20.7 × 10^{12} cu. ft. of gas, for an average of 1.81 × 10^{8} cu. ft. of gas produced per well**. On this basis, the annual production of about 500 "average" wells is required to supply the 1000 Mw(e)

---

*General industry-wide estimate based on private communication with industry source.

**Calculated from data presented in the 1969 Minerals Yearbook(1).

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

〰〰→	ELECTRICAL ENERGY
- - - - →	AIRBORNE RELEASE
⇨	LIQUID EFFLUENT
➡	SOLID EFFLUENT

Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
MW(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSIBLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
EPA Project Officer: Paul H. Gerhardt
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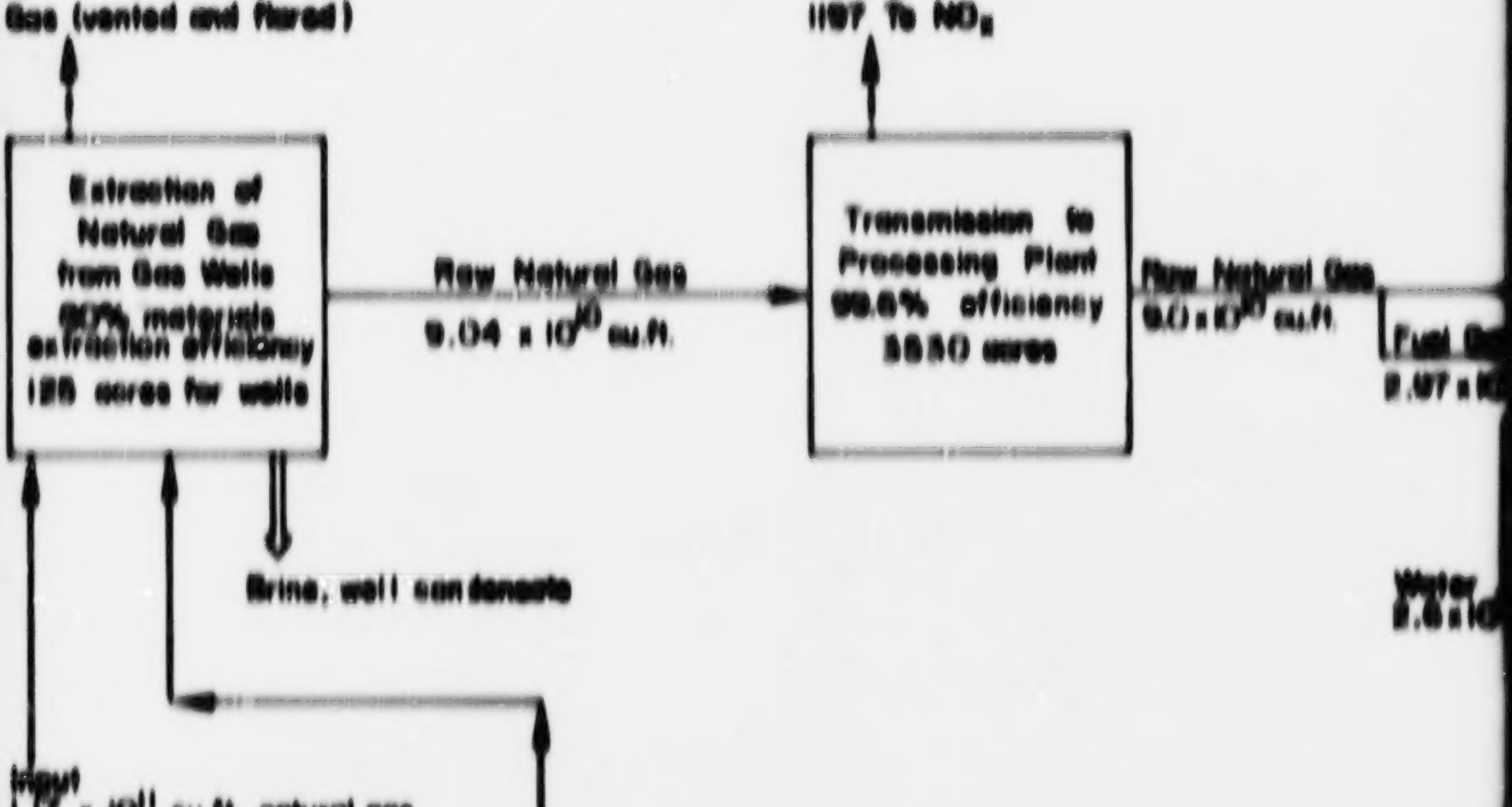
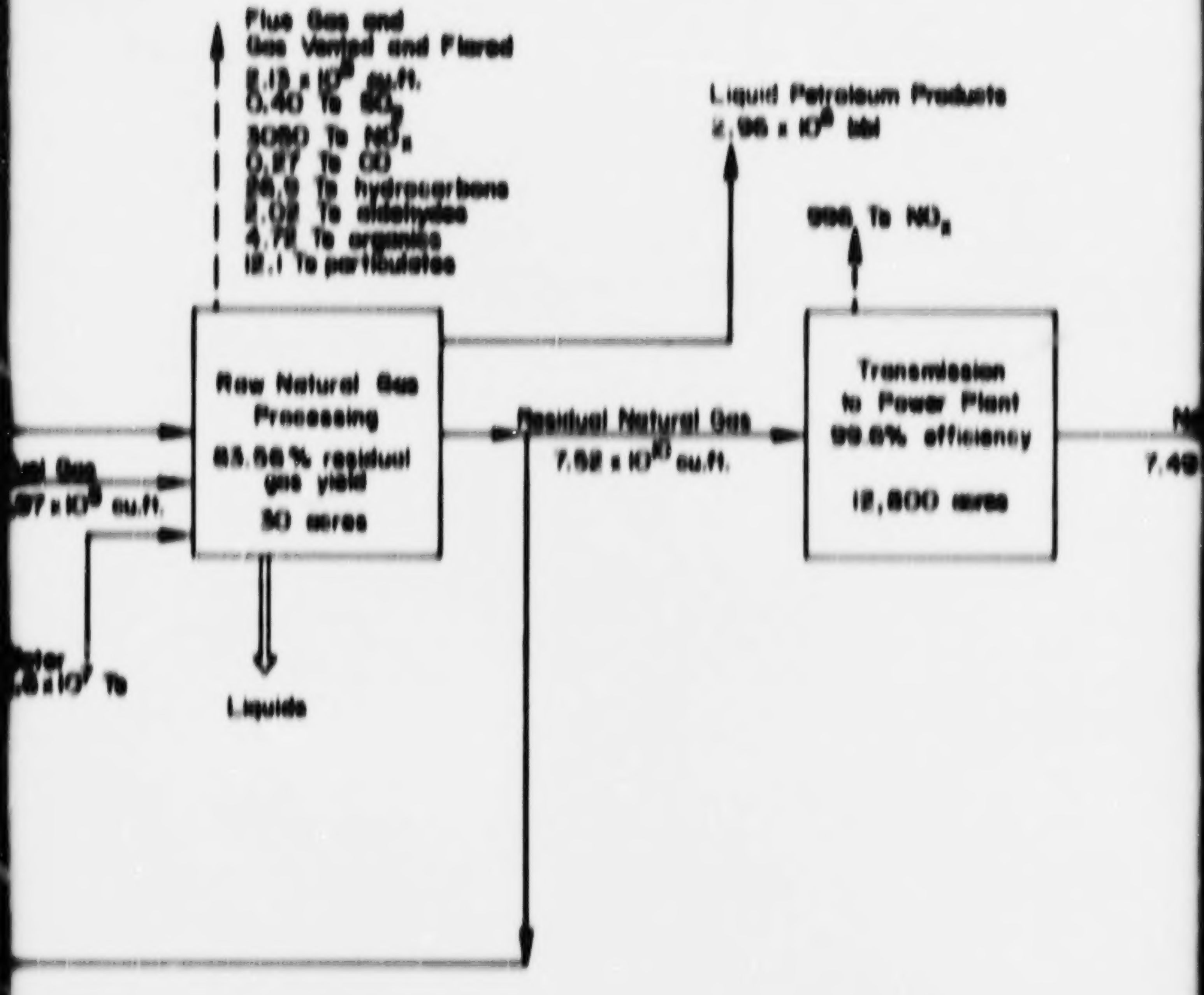
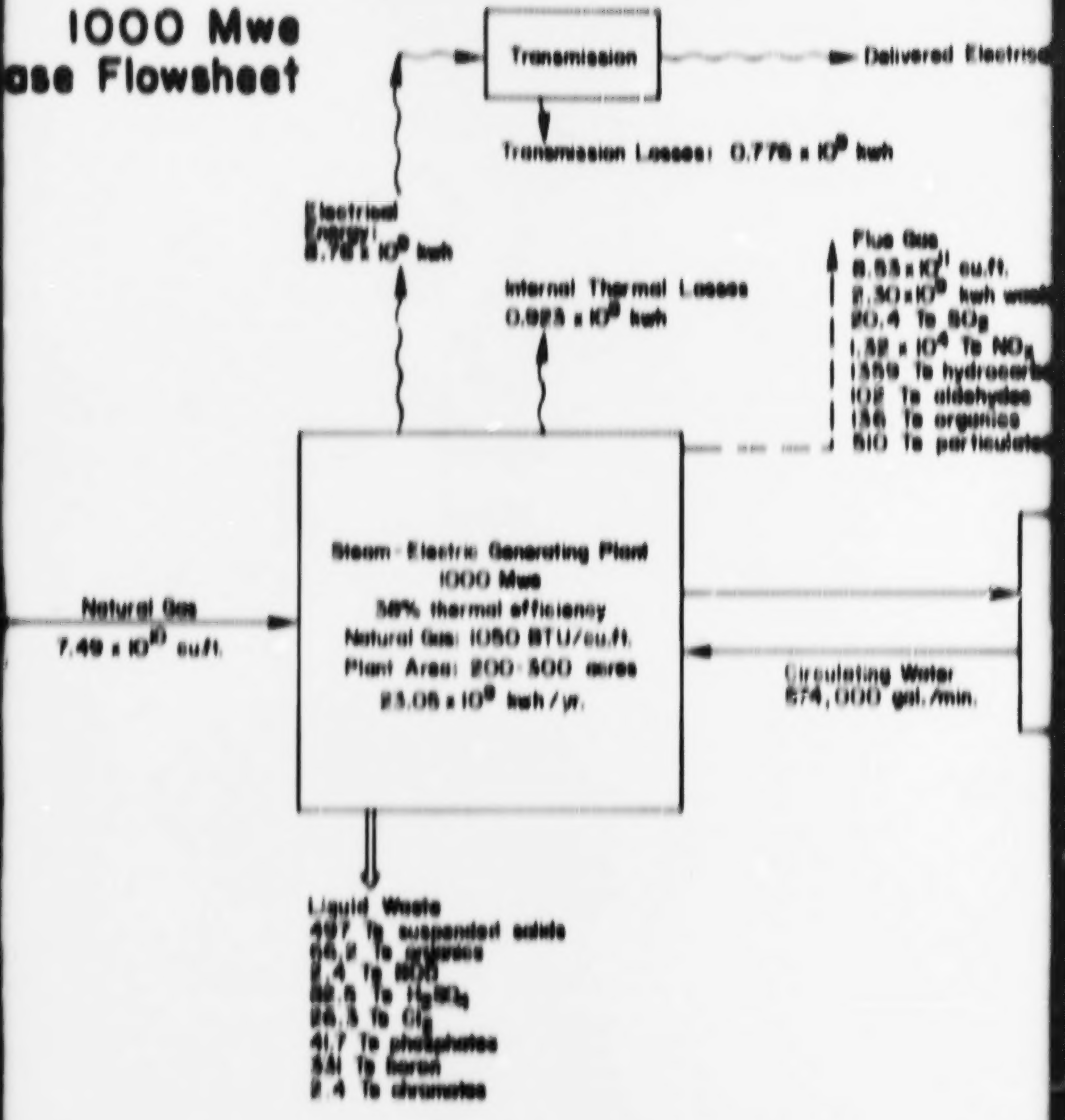

Gas (vented and flared)
Extraction of Natural Gas from Gas Wells 80% materials extraction efficiency 125 acres for wells
Raw Natural Gas 9.04 x 10^10 cu.ft.
1197 To NOx
Transmission to Processing Plant 99.5% efficiency 5550 acres
Raw Natural Gas 9.0 x 10^10 cu.ft.
Fuel Ga
2.07 x 10
Water
2.6 x 10
Brine, well condensate
Input 1.17 x 10^11 cu.ft. natural gas
Returned to Underground Gas Formations 6.91 x 10^9 cu.ft.

Figure 5.1

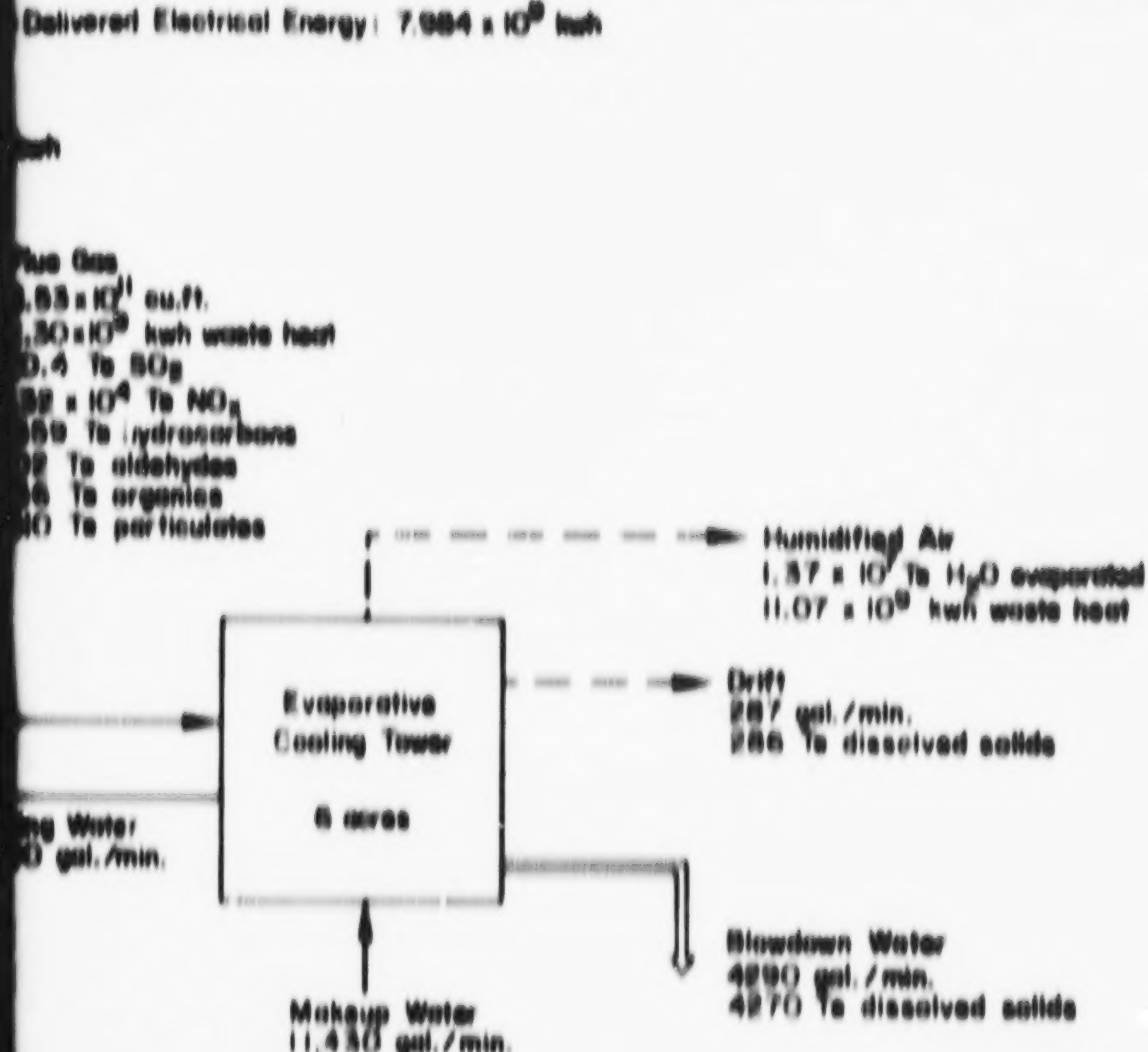
Natural Gas Power Plant 10
Material And Environmental Release


Flue Gas and
Gas Vented and Flared
2.12×10^{9} cu.ft.
0.40 Te SO_2
3080 Te NO_x
0.27 Te CO
26.9 Te hydrocarbons
2.02 Te aldehydes
4.72 Te organics
12.1 Te particulates
Liquid Petroleum Products
2.96×10^{6} bbl
996 Te NO_x
Raw Natural Gas Processing
85.56% residual gas yield
30 acres
Residual Natural Gas
7.52×10^{10} cu.ft.
Transmission to Power Plant
99.6% efficiency
12,800 acres
7.49
al Gas
97×10^{9} cu.ft.
ater
8×10^{7} Te
Liquids

1000 Mwe
ase Flowsheet



Transmission
Delivered Electric
Transmission Losses: 0.776 x 10⁹ kwh
Electrical Energy: 8.76 x 10⁹ kwh
Internal Thermal Losses
0.925 x 10⁹ kwh
Flue Gas
8.55 x 10¹¹ cu.ft.
2.30 x 10⁹ kwh wa
20.4 Te SO₂
1.82 x 10⁴ Te NOₓ
1559 Te hydrocarb
102 Te aldehydes
156 Te organics
510 Te particulate
Steam-Electric Generating Plant
1000 Mwe
38% thermal efficiency
Natural Gas: 1050 BTU/cu.ft.
Plant Area: 200-300 acres
23.05 x 10⁹ kwh/yr.
Natural Gas
7.49 x 10¹⁰ cu.ft.
Circulating Water
674,000 gal./min.
Liquid Waste
497 Te suspended solids
66.2 Te organics
2.4 Te BOD
89.5 Te H₂SO₄
26.5 Te Cl₂
41.7 Te phosphates
534 Te boron
2.4 Te chromates


Delivered Electrical Energy: 7.984 x 10^9 kwh
kwh
Flue Gas
.55 x 10^11 cu.ft.
.30 x 10^9 kwh waste heat
0.4 Ts SO2
32 x 10^4 Ts NOx
059 Ts hydrocarbons
02 Ts aldehydes
06 Ts organics
00 Ts particulates
Humidified Air
1.37 x 10^7 Ts H2O evaporated
11.07 x 10^9 kwh waste heat
Drift
287 gal./min.
286 Ts dissolved solids
Evaporative Cooling Tower
6 acres
ng Water
0 gal./min.
Blowdown Water
4290 gal./min.
4270 Ts dissolved solids
Makeup Water
11,430 gal./min.

TEKNEKRON, INC.

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

power plant. Based on one quarter acre of land per well*, 125 acres are required, assuming the wells produce continuously during the power plant operating life and neglecting additional requirements for exploration activities associated with this amount of production.

Quantities of salt water and condensed hydrocarbons are separated from the gas at the well head of high-pressure gas wells, however, no quantitative estimates are available.

In the processes of drilling and proving gas wells, gas is lost at the well head by venting and flaring, and by leaks and accidents. The practice of venting is being curtailed by the industry. Quantitative estimates of effluents are presently not available.

Unknown quantities of pollutants are emitted by power equipment used to drive pumps at gas wells.

5.3 Transmission of Raw Gas to Processing Plant

An overall industry-wide estimate of 99.65 efficiency is used for gas pipeline transmission**. Most of the loss is due to the use of fuel at compression stations.

An estimate of the land area required for field-gathering mains and transmission pipe is obtained as follows. The 1969 Minerals Yearbook reported the total mileage of gas-field-gathering mains as 64,400 miles[1]. The calculated share of the marketed gas production represented by the fuel supply for the 1000 Mw(e) power plant is 0.288%. Scaling the total field-gathering pipeline mileage to this fraction yields 250 miles of pipeline required for the gas for the present flowsheet. On the assumption that the land required for gas transmission pipelines is 14 acres per mile and that a 10-acre pumping station is required for every 75 miles of pipeline(2), 3,530 acres are required for transmission. Pipeline right of way is generally available for other limited beneficial uses after construction.

---

*An assumption for the purposes of this paper which includes land for well structures and associated equipment.

**Calculated from data presented in the 1969 Minerals Yearbook[1].

Assuming that 0.4% of the transmitted gas is consumed as fuel, and using an emission factor of 7,300 lbs. NO_x per 10^6 cu. ft. of fuel gas consumed(3), 1197 Te/yr of NO_x are produced in transmitting gas from wells to the gas-processing plant.

5.4 Raw Gas Processing

Of the raw gas leaving the well head, 99.6% or 9.0×10^{10} cu.ft./yr arrives at the processing plant. On an industry-wide basis in 1969, 83.6% of the raw gas input to processing plants was sold as residual gas*, leaving 7.52×10^{10} cu.ft./yr of fuel transmitted to the power plant in the present flowsheet.

Typical land requirement for a modern gas processing plant is approximately 30 acres(4).

Water requirements for natural gas processing in 1962 were 8.425×10^{11} gal of water(5) to process 11.089×10^{12} cu. ft. of raw natural gas(6). The processing of 9.0×10^{10} cu.ft./yr of raw gas would then require

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*Calculated from data presented in the 1969 Minerals Yearbook(1).

2.60 × 10^7 Ts/yr of water, a large portion of which is reusable.

On an industry-wide basis in 1969, 3.3% of the raw gas input to gas processing plants was used to fuel the processing operations*. From this result, 2.97 × 10^9 cu. ft. of gas fuel is required for processing the annual amount of 9.0 × 10^{10} cu. ft. of raw gas.

Of the 2.97 × 10^9 cu. ft. of gas consumed as fuel in the processing plant, it is assumed that one-half is used in gas engines and one-half used in process boilers. The primary pollutant produced by the gas engines is NO_x. Using an emission factor of 4,000 lb. NO_x per 10^6 cu. ft. of gas consumed in processing plant gas engines(8), 2697 Ts of NO_x are emitted. For the 1.48 × 10^9 cu. ft. of gas consumed in process boilers, the emission factors and calculated amounts of pollutants are shown in Table 6.1.

---

*Calculated from data presented in the 1969 Minerals Yearbook(1), p. 740.

Table 8.1

Gaseous Effluents from Natural Gas Processing Plant

Pollutant	Emission factors[3] lb/10^6 cu. ft.	Annual quantities associated with fuel processing for a 1000 MW(e) power plant To/yr
Particulates	15	10.13
SO_x	0.6	0.40
CO	0.4	0.27
Hydrocarbons	40	27.00
NO_x	200	135.00
Aldehydes	3	2.03
Organics	7	4.73

The total yearly amount of NO_x from gas engines and process boilers is estimated to be 2052 To.

Natural-gas processing produces by-product natural-gas liquids at the rate of 38.8 bbl per million cu. ft. of gas processed*, corresponding to 2.06 x 10^6 bbl of liquid petroleum products for the present flowsheet.

Some of the natural gas produced from wells is returned to the gas bearing formation to stimulate flow and enhance production. Based on industry-wide data and scaling to the production required for the 1000 MW(e) power plant, 6.01 x 10^9 cu. ft. of gas is returned annually to the gas field for reinjection*.

---

*Calculated from data presented in the 1969 Minerals Yearbook[1], p. 769.

Of the raw gas entering processing plants, 0.0075 is flared or vented to the atmosphere*; this corresponds to the venting and flaring of 2.13 x 10^8 cu.ft./yr for the present flowsheet.

5.5 Transmission of Residual Gas to Power Plant

Residual natural gas from the processing plant is transmitted by pipeline to the power plant at the rate of 7.66 x 10^{10} cu.ft./yr. The pipeline transmission efficiency used is the same as the efficiency for transmission from wells to processing plants, i.e. 99.63.

In 1969, there were 252,940 miles of gas transmission lines in the U.S.[1] Scaling the total transmission pipeline mileage, the industry fraction of 0.[illegible] associated with this flowsheet (cf. Section 5.2) yields 997 miles of pipeline for transmitting fuel from the processing plant to the 1000 Mw(e) power plant. Based on data presented in Section 5.3 transmission requires 12,[illegible] acres of land and results in the consumption of 2.8 x 10^8 cu.ft./yr of natural gas as transmission fuel, and the production of 900 Tn/yr of NO_x.

5.6 Power Plant Operation

The 1000 Mw(e) power plant is assumed to have an overall thermal efficiency of 38% and a 100% load factor, with a thermal energy budget given in Table 5.1. For a natural-gas heating value of 1030 Btu/cu.ft.[2], the annual fuel supply is 7.63 x 10^{10} cu. ft.

---

*Calculated from data presented in the 1969 Minerals Yearbook[1], p. 749.

An estimated 100 to 200 acres is required for the power plant[7], which is less than that for coal-fired power plants because of the absence of fuel and ash storage.

Liquid wastes associated with boiler feedwater treatment and blowdown are assumed to be identical to those for the coal-fired power plant, summarized in Table 6.5.

6.7 Flue Gas Effluents

Combustion of the natural-gas fuel results in 8.08 x 10^{11} cu.ft./yr of flue gas*. A typical particulate emission rate for natural-gas-fired power plants is 15 lb. per 10^6 cu. ft. of gas consumed[8], resulting in 510 Tn/yr emitted from the stack. No fly ash removal is required.

The gaseous effluents from the power plant stack are summarized in Table 6.8.

Table 6.8

Gaseous Effluents from Natural-Gas-Fired Power Plant - 1000 MW(e)

	Emission factors[8] lb. per 10^6 cu. ft.	Yearly effluents Tn/yr
SO_2	0.6	20.4
Hydrocarbons	40	1,360
NO_2	390	13,000
Aldehydes	3	100
Organics	4	136

---

*Calculated from data presented in Reference (8).

6.8 Condenser Cooling

It is assumed that condenser cooling is provided by evaporative cooling towers. The quantities are identical to those for the 1000 Mw(e) coal-fired power plant summarized in Section 5.2.

REFERENCES

1. U. S. Department of the Interior, "Minerals Yearbook - 1969," vols. I-II (1971).

2. U. S. Federal Power Commission; Opinion No. 612, Arkansas Louisiana Gas Company, Docket No. CP 70-207, p. 6 (February, 1972).

3. U. S. Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors" (February, 1972).

4. U. S. Federal Power Commission, Docket No. CP72-8, "Environmental Impact of Columbia LNG Corporation Gas Processing Plant," p. 4 (November, 1971).

5. U. S. Department of the Interior, "Water Use in Mineral Industry," Bureau of Mines Information Circular 8285, p. 28 (1966).

6. U. S. Department of the Interior, "Minerals Yearbook - 1962," vol. II, p. 345 (1963).

7. Energy Policy Staff, Office of Science and Technology, "Considerations Affecting Steam Power Plant Site Selection," p. 11 (December, 1968).

8. Esso Research and Engineering Co., "Systems Study of Nitrogen Oxide Control Methods for Stationary Sources," Final Report Vol. II, p. 1-16 (November, 1969).

6. WASTE HEAT REJECTION

6.1 Once-Through Cooling Water

Once-through cooling involves withdrawing large quantities of surface water from a river, large lake, estuary, or ocean and returning that surface water after it has passed through the steam condenser. The required quantity of cooling water is proportional to the product of the waste heat rejection rate and the temperature rise. Temperature increases of 10 to 30°F are typical. A temperature rise of 16°F has been assumed in the present analysis, resulting in a water requirement of 880,000 gal/min for the light-water power reactor and 574,000 gal/min for the coal-fired power plant, as shown on the flowsheets Figures 6.1 and 6.2.

Because of the enormous quantities of water circulated, the heated water must be discharged at a point well removed from the intake location to avoid recirculation of the heated water. The intake structure is usually submerged and extends far from the shoreline. The intake must be designed with screens and low-velocity diffusers to minimize the loss of fish by physical impact. In some installations submerged outfalls for discharge water are necessary to minimize locally heated areas.

Besides being the most economical cooling technology when sufficient quantities of surface water are available, once-through cooling has the advantage that it offers large quantities of discharge water for the dilution of liquid effluents. For example, the indicated yearly releases of tritium and non-tritium radioactivity from the light-water nuclear

Figure 8.1

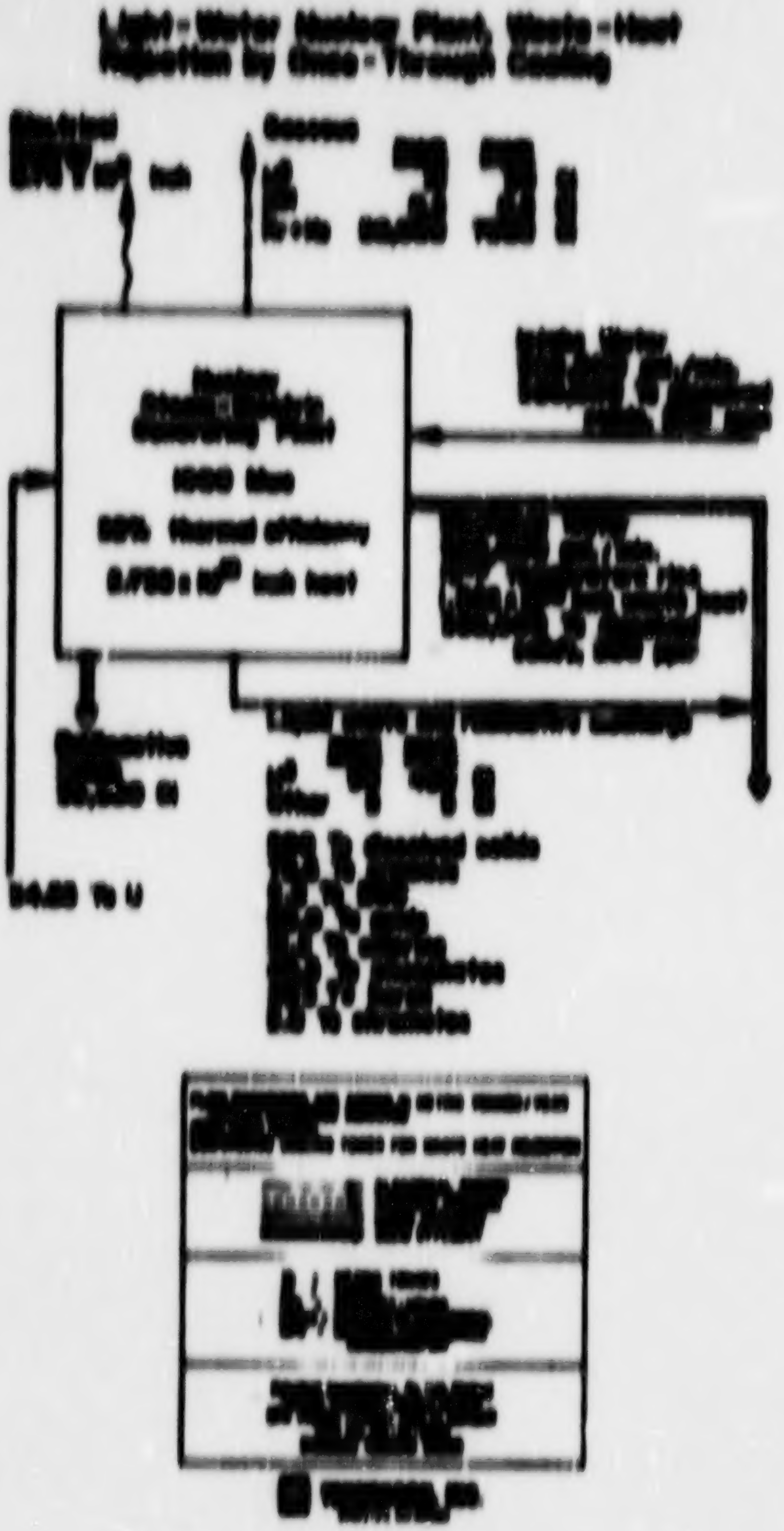
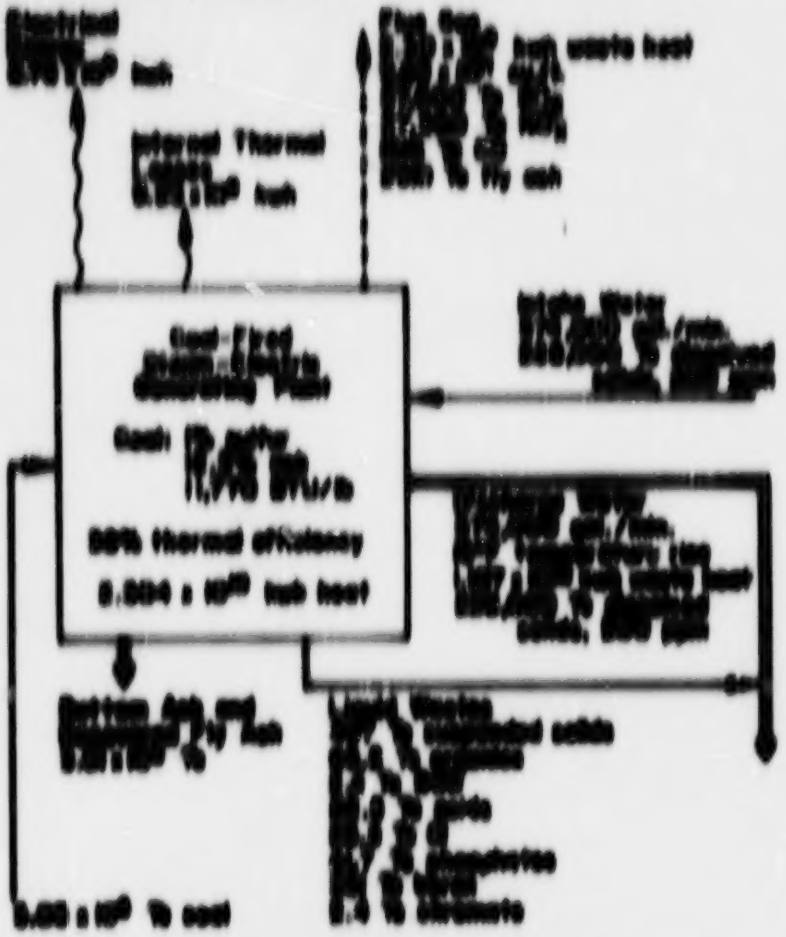
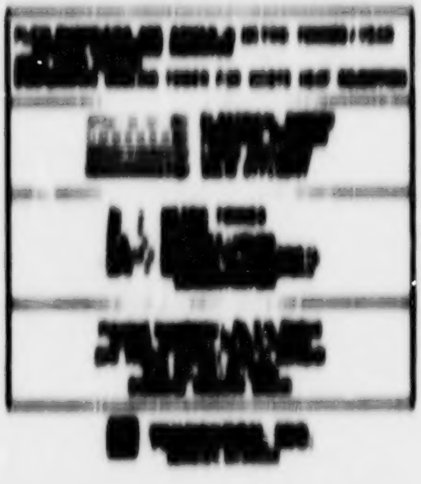


Figure 8.8

Coal-Fired Power Plant, Waste-Heat Rejection by Once-Through Cooling


Electrical Energy
kwh
Internal Thermal Losses
kwh
Flue Gas
kwh waste heat
fly ash
Coal-Fired Steam-Electric Generating Plant
Coal:
BTU/lb
38% thermal efficiency
kwh heat
Intake Water
gal/min
Discharge Water
gal/min
kwh waste heat
Bottom Ash and
kwh
Liquid Wastes
suspended solids
phosphates
chromate
to coal



plant, when diluted in the discharge water, result in concentrations well below the proposed Appendix I, 10 CFR 50, design-objective concentrations of 5×10^{-6} microcuries/cc for tritium and 2×10^{-8} microcuries/cc for non-tritium radionuclides in liquid effluents. Also, the concentration of dissolved salts in the liquid discharge is the same as that in the intake; there is no salt concentration by evaporation that occurs in evaporative cooling towers and cooling ponds. There are no plumes of humidified air, as from evaporative cooling, which can contribute to icing and fogging. The visual profile is the least obtrusive of all the cooling technologies. Some environmental benefits are claimed as a result of the rapid growth of certain fish species in the vicinity of the heated outfall, but these species appear to be sensitive to the loss of heated discharge water during plant shutdown.

The discharge of large quantities of hot water does change the ecology of the water in the vicinity of the discharge; the oxygen content is lowered, metabolic rates are altered, and the growth of undesirable bacteria is enhanced. Also various forms of aquatic life, such as fish larvae, flow through the intake screens and through the condenser tubes, resulting in high mortality rates of these species.

6.2 Evaporative Cooling Towers and Spray Cooling

Equipment for evaporative cooling may consist of a mechanical draft cooling tower, a natural draft cooling tower, or a spray cooling pond or canal. For the purpose of this report, the rate of circulation of water between the steam condenser and the evaporative cooler is calculated on the basis of an assumed 10°F temperature rise in the water as it flows through the condenser. Consequently, the circulation rate is numerically equal to the flow rate for once-through cooling, which was calculated on the basis of the same temperature rise.

To calculate the water evaporation rate it was assumed that air enters the evaporative cooler at a temperature of 80°F and a relative humidity of 60%, corresponding to a wet bulb temperature of 69.4°F. Using thermodynamic data(1) for air at various temperatures and water content, the dissipative heat load can be translated into a volumetric flow rate of air and a rate of evaporation of water. The results are shown on the flow sheets, Figures 6.3 and 6.4.

Since the water make-up to the cooling system contains dissolved solids which are not removed in the evaporation process, it is necessary that there be a water discharge, or blowdown, to keep the dissolved solids from building up to a high concentration in the water circulation system. The blowdown rate depends upon the salt concentration in the make-up water and the tolerable salt concentration in the circulating system and the blowdown. Typical blowdown rates are of the order of 1% of the circulation rate.

Drift, or airborne entrained water containing dissolved solids, can be an important environmental pollutant from evaporative cooling towers. The amount of drift varies with tower design and local wind conditions. Because of their taller stacks and lower air velocities, the natural draft towers operate with less drift than do mechanical draft

Figure 6.8

Light-Water Nuclear Plant, Waste-Heat Rejection by Evaporative Cooling

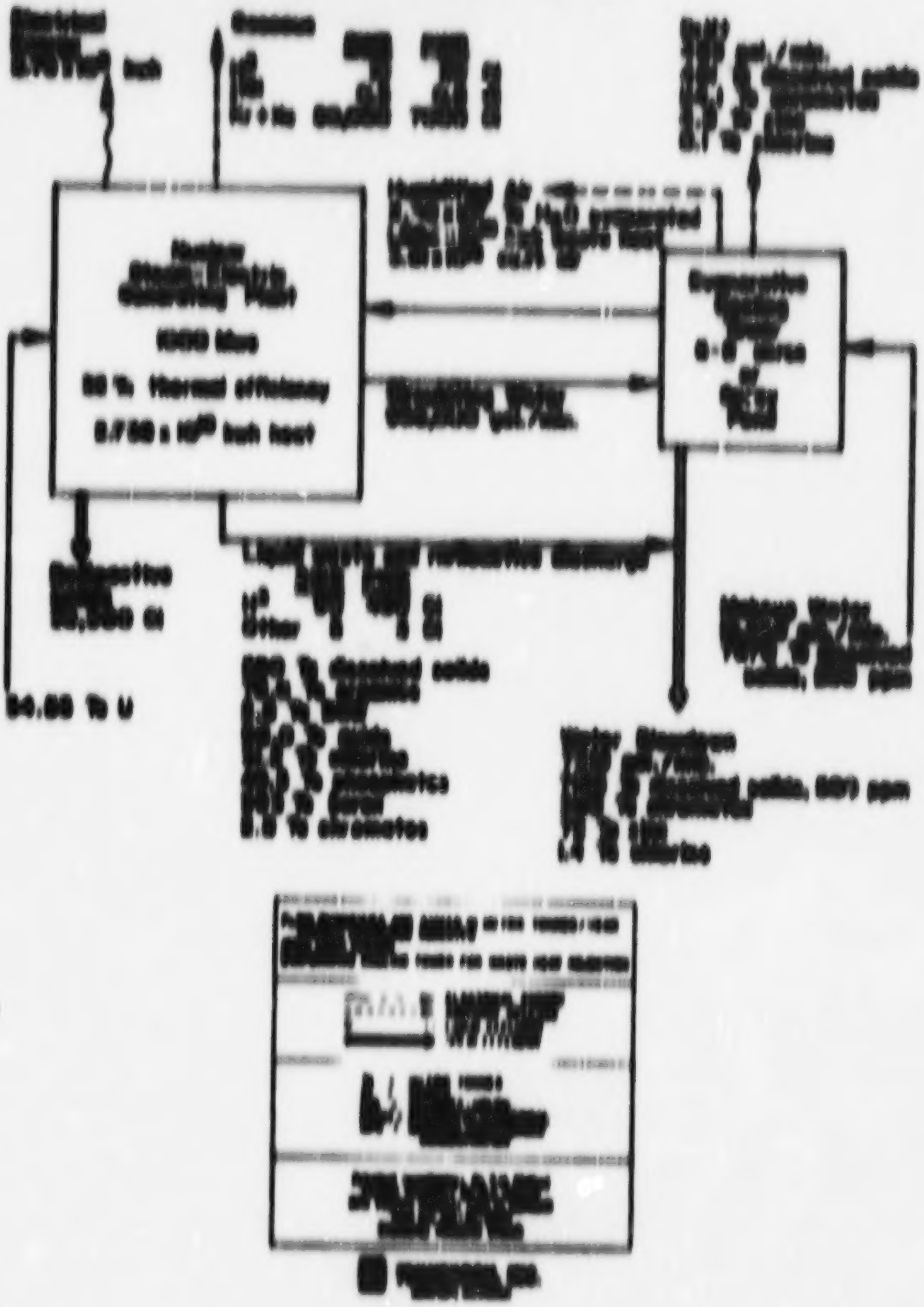
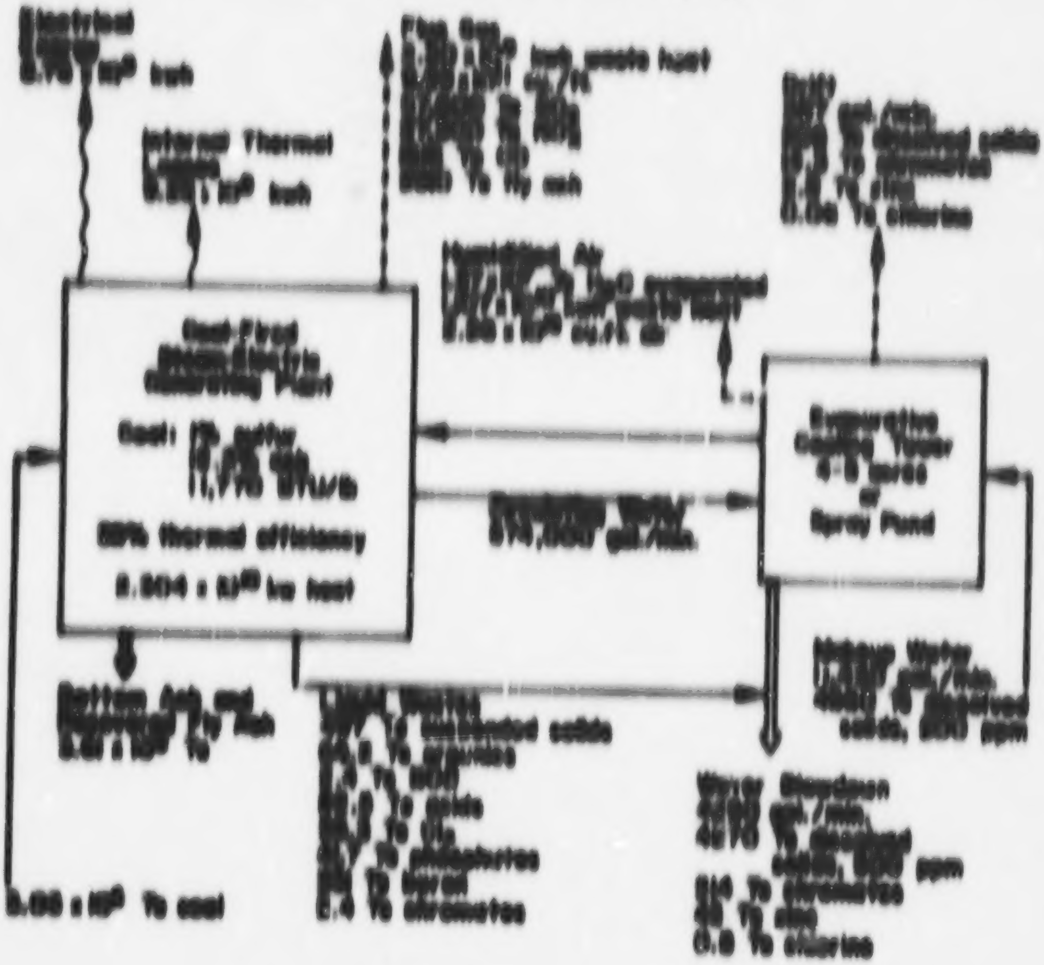

Nuclear Generating Plant
thermal efficiency
Evaporative Cooling Tower
Liquid waste and radioactive discharge
Radioactive
Intake Water
Water Discharge
Teknekron, Inc.

Figure 6.4

Coal-Fired Power Plant, Waste-Heat Rejection by Evaporative Cooling


Electrical Energy
kwh
Internal Thermal Losses
kwh
Flue Gas
kwh waste heat
To fly ash
Humidified Air
H₂O evaporated
waste heat
cu.ft. air
Drift
gal./min.
dissolved solids
To zinc
0.06 To chlorine
Coal-Fired Steam-Electric Generating Plant
Coal: 1% sulfur
11,770 BTU/lb
38% thermal efficiency
kw heat
Evaporative Cooling Tower
4-8 acres
or
Spray Pond
Circulating Water
574,000 gal./min.
Makeup Water
gal./min.
dissolved solids, ppm
Bottom Ash and Recovered Fly Ash
To
Liquid Wastes
To suspended solids
To organics
To acids
To oil
To phosphates
To boron
To chromates
Water Blowdown
gal./min.
dissolved solids, ppm
To chromates
To zinc
0.8 To chlorine
To coal

towers. Drift losses are probably greatest for spray ponds and spray canals[7]. Drift loss rates are usually expressed as a percentage of the circulating water flow. For evaporative cooling towers drift percentages as high as 0.2% and as low as 0.002% are quoted[2,3,4]. The current drift warranty on large natural-draft cooling towers is 0.1%[2]. A nominal[3] drift loss from mechanical-draft towers of 0.005% of the recirculating flow is used in the present analysis. For the reference light-water nuclear power plant this corresponds to a drift loss of 483 gallons per minute.

The concentration of dissolved solids in the circulating system and in the blowdown water and drift depend upon the rate of water evaporation, the drift rate, the blowdown rate, and the concentration of solids in the water make-up. In the flowsheets shown here the make-up water is assumed to contain a nominal concentration of 200 parts per million (ppm) of dissolved solids. It is assumed that the concentration in the blowdown water is limited to 500 ppm, resulting in a typical concentration ratio of 2.5 for the salt concentration in blowdown and drift relative to the concentration in water make-up.

Higher salt concentrations than the 200 ppm concentration considered in this reference design are found in many inland waters. For example, the Colorado river, which supplies large quantities of water to the southwestern United States, contains an average salinity of 600 ppm as it flows through Arizona, increasing to 850 ppm at the Imperial Dam. These salt contents are expected to increase to 900 ppm and 1340 ppm by the year 2000 unless measures are taken to control the river's salinity[5].

Drift becomes a more serious environmental contaminant when salt water is used as make-up. Typical sea water contains 18,000 ppm sodium chloride, 400 ppm calcium, 600 ppm magnesium, and 25 to 40 ppm total carbon(8). Distribution of even several hundred gallons per minute of sea water over adjacent terrain as drift presents ecological problems, and these are amplified by the concentrating effect of evaporation (2.5 times in the present example).

The following quantities in Table 6.1 are calculated for the evaporative cooling system for the reference light-water nuclear power plant.

Table 6.1
Water Consumption for Evaporative Cooling Tower, Light-Water Nuclear Plant

Waste heat dissipated: 1.86 x 10^{10} kwh/yr

Water evaporation rate: 11,540 gal/min

	Flow rate gal/min	Dissolved solids Te/yr
Make-up water	19,230	7500
Drift	483	400
Blowdown water	7,210	7100

The salt concentrated by evaporation appears as the increased concentration of dissolved solids in the blowdown and drift. The amount concentrated is the product of the quantity of water evaporated and the concentration of dissolved solid in the make-up water. For the light-water reactor reference design this corresponds to 6000 Te/yr. The above data are scaled according to the amount of waste heat dissipated to obtain the evaporative cooling quantities shown in the flowcharts.

In addition to the concentrated dissolved solids, the drift and blowdown water from evaporative cooling systems will contain chemicals added to the circulating water to prevent scale, to control corrosion, and to prevent microbiological growth. Sulfuric acid is usually added to lower the pH, reducing the deposition of dissolved solids as scale on the condenser heat transfer surfaces. Corrosion inhibitors generally are a combination of cathodic and anodic inhibitors. The chromate-based inhibitors have been the most widely accepted(8). Where it has been necessary to discontinue the use of environmentally hazardous chromates, blends of zinc sulfate and lignosulfonates are used. Other chemical combinations for inhibiting corrosion are chromates-zinc, chromates-hexametaphosphates, chromates-organics, chromates-hexametaphosphates-zinc, chromate-zinc-organic, organic-zinc, nitrites, sodium silicates, and sodium silicates with dispersives and anti-nucleating agents. The increased use of zinc-containing chemicals may result in requirements for ion-exchange treatment of the water blowdown to reduce the likely toxicity to fish. These chemicals appear in the drift losses. For example, at a chromate concentration of 20 ppm and zinc concentration of 5 ppm in the circulating water, the calculated drift for the reference light-water nuclear power plant carries 24.1 Te/yr of chromates and 4.8 Te/yr of zinc.

Biocides to kill microorganisms in the cooling tower and circulation system have, in some instances, consisted of copper compounds, tributyl tin, and chlorophenates[10]. These have proved dangerous to the microorganisms in the surface waters to which the blowdown water is discharged and have been supplanted by shorter-lived biocides, such as chlorine, bromine, and acrolein, or by other biocides which are less harmful after dilution of the blowdown water. Free-chlorine residuals in the circulating water may be in the concentration range of 0.1 to 1.0 ppm[10,11]. On the basis of 0.1 ppm, the free-chlorine residuals discharged in the reference light-water nuclear plant amount to 0.1 Te/yr in the drift and 1.4 Te/yr in the water blowdown.

Additional chemical contaminants are introduced when wood packing is used in the cooling tower to obtain increased surface area for mass transfer and heat transfer. To reduce deterioration the wood can be impregnated with copper and arsenic salts, but some copper arsenide can be expected to leach into the circulating water. Creosote impregnation has also been used[10]. In modern cooling tower construction non-wood packing materials such as transite, ceramics, and plastic laminates are utilized.

Increased oxygen content of the evaporative cooling blowdown water, resulting from multipass contacting of the circulating water with air, is an environmental benefit.

The mixing of the large quantities of highly humidified air from the evaporative cooling system can, under some conditions, result in water precipitation, in the form of fog, rain, or ice. It may also result in local air recirculation. The local effects may be less for natural draft cooling towers because of the great height at which the humidified air is released. Even in this case, however, humidity increases in the surrounding air can be detected several miles down-wind of the cooling tower(4). Even under those atmospheric conditions when there may be no visible plumes from cooling towers, the general humidity level may be raised when conditions of poor atmospheric mixing prevail. Subsequent nocturnal cooling may produce extensive fog in areas not necessarily contiguous with the towers themselves. Also, on days when cumulus clouds form naturally, there can be a tendency for clouds to initiate in the large plumes of humidified air discharged from the evaporative cooling towers and to propagate down-wind as cloud streets, with the possibility of increased precipitation(10).

For fossil-fueled power plants with elevated discharges of combustion gases, the plumes of combustion gas will tend to merge with the plume of humidified air from the cooling tower. The increased humidity can affect gaseous air pollutants in the flue gas. For example, sulfur dioxide in the discharged flue gas can slowly oxidize to sulfur trioxide as it propagates downwind. The sulfur trioxide will react with water vapor to precipitate water droplets containing sulfuric acid, giving rise to "acid rain"(21).

The relatively small volume of discharge water from evaporative cooling systems creates some problem in the dilution-dispersal of liquid wastes. This is illustrated in the case of tritium and non-tritium radionuclides in liquid effluents in light-water nuclear power plants, discussed in Section 6.7 of this report.

Land area for spray cooling ponds or spray canals is calculated on the basis of a nominal water loading of 800 lb/hr per square foot of pond or canal area[(7)]. This results in a land area requirement comparable to that for forced draft and natural draft evaporative cooling towers. The relatively large height, 400 to 600 ft., of the natural-draft cooling tower has become a visual impact consideration in some instances.

6.8 Cooling Ponds

The evaporative loss for cooling ponds is calculated on the basis of data quoted by Olsson and Doyle[(7)] and by Jacks and Drew[(10)] for evaporation rates for cooling towers and cooling ponds. Their data, translated to gallons evaporated per unit of waste heat to be disposed of, are as follows:

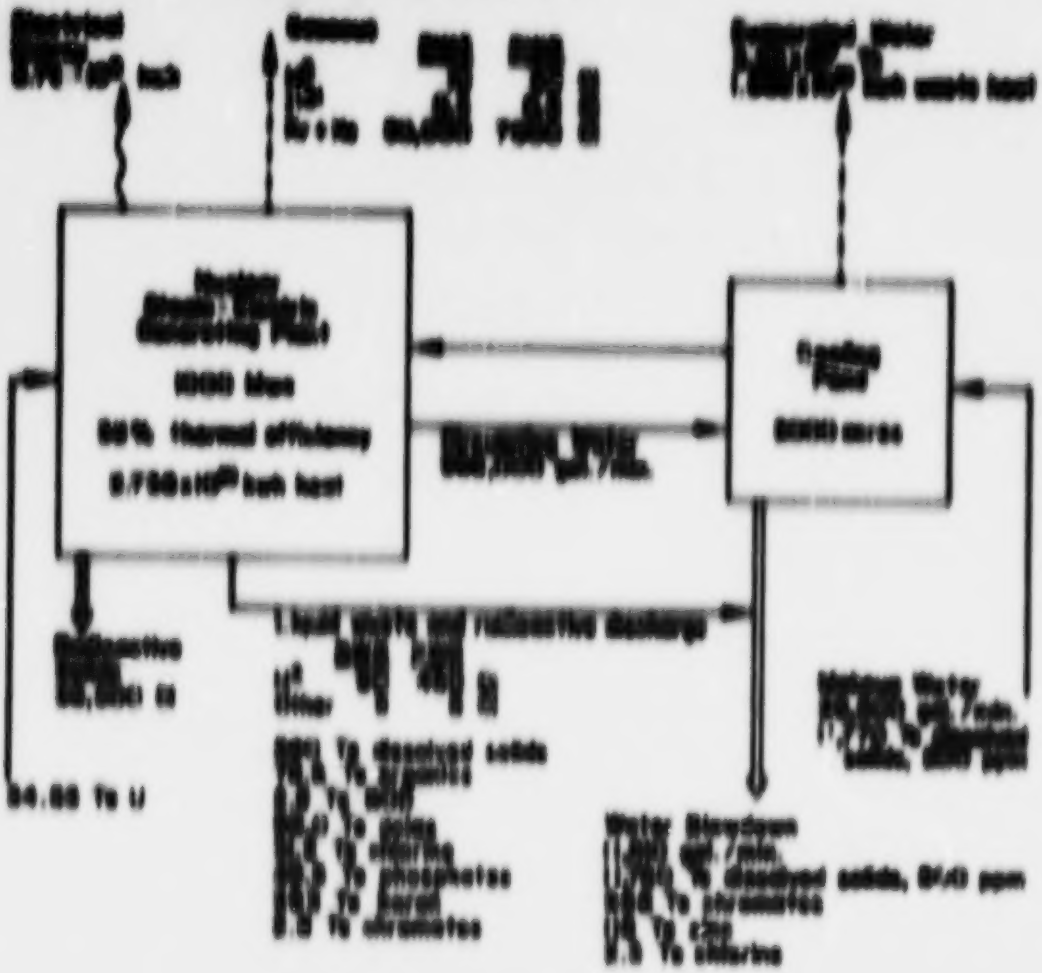
cooling pond area acres per megawatt of waste heat	specific evaporation gallons per kwh of waste heat
0.47	0.40[(7)]
0.94	0.60[(7)]
1.12 (Benton Cty., Wash.)	0.42[(10)]
2.08 (Lake Arlington, Texas)	0.50[(10)]

By comparison, for the evaporative cooling tower we have calculated a specific evaporation rate of 0.325 gallons per kwh of waste heat. The total evaporation rate from cooling ponds is greater than that for cooling towers because of the additional surface water exposed to the sun. The pond surface is also exposed to rainfall, and for very large ponds in regions of high rainfall this may reduce the quantity of make-up water. For example, for the pond area of 1.7 acres per megawatt of waste heat, the evaporation of 0.48 gallons per kwh corresponds to a total loss rate of 102 inches of water per year.

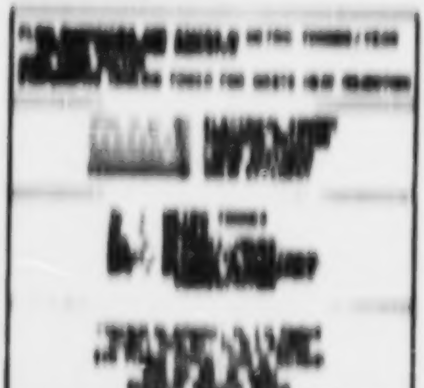
Flowsheets for waste-heat rejection by cooling ponds are shown in Figures 6.5 and 6.6. In calculating the quantities on the flowsheets we have used a pond area of 0.04 acres per megawatt and an evaporation rate of 0.50 gallons per kwh of waste heat. The rates of water make-up and blowdown are calculated on the assumption that the concentration of dissolved solids in the make-up and discharge water are the same as those calculated for the evaporative cooling towers.

Figure [illegible]

Light-Water Nuclear Plant, Waste-Heat Rejection by Cooling Pond



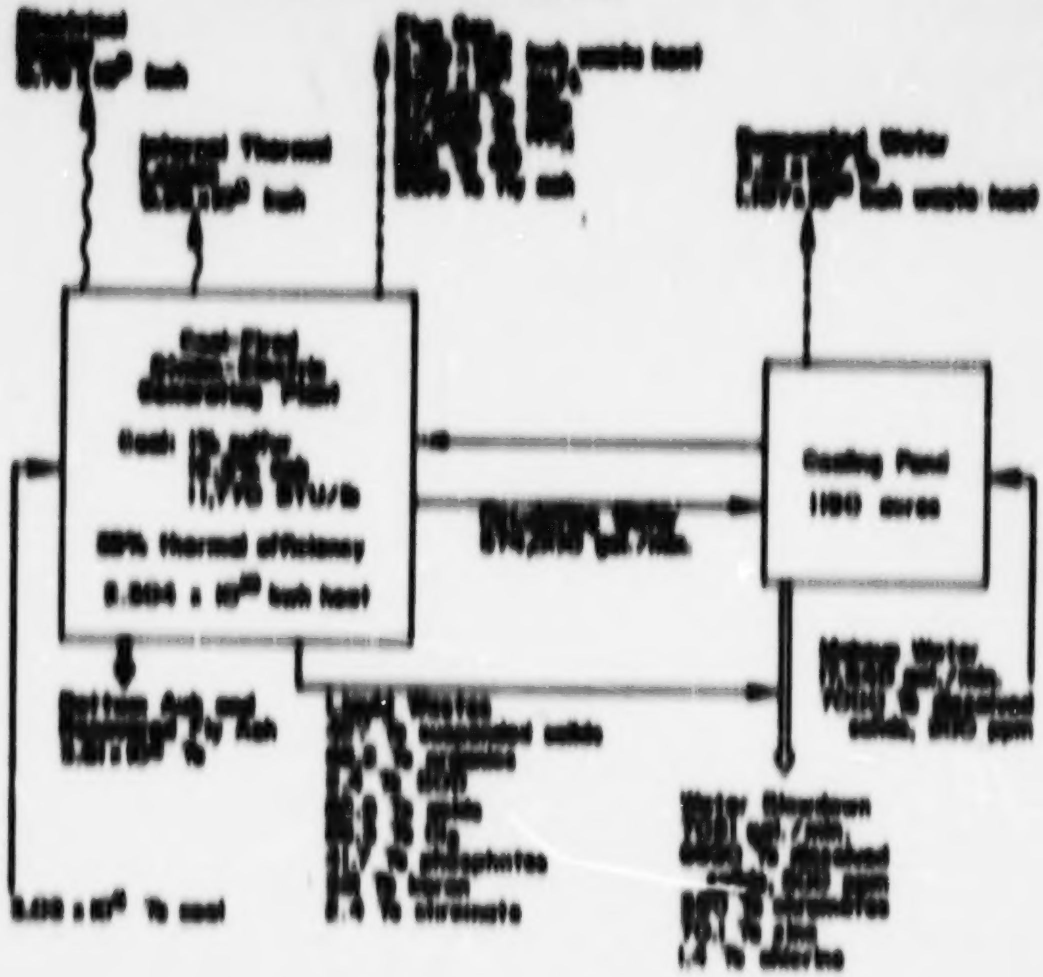
Electrical Energy
Gaseous
Evaporated Water
waste heat
Nuclear Steam-Electric Generating Plant
1000 Mwe
33% thermal efficiency
kwh heat
Cooling Pond
acres
Liquid waste and radioactive discharge
Radioactive
Makeup Water
Water Blowdown
% dissolved solids
% chromates
% chlorine
% phosphates
% boron
% zinc



Teknekron, Inc.

Figure 6.6

Coal-Fired Power Plant, Waste-Heat Rejection by Cooling Pond


Electrical Power
kwh
Infrared Thermal Losses
kwh
Flue Gas
kwh waste heat
fly ash
Evaporated Water
kwh waste heat
Coal-Fired Steam-Electric Generating Plant
Coal:
BTU/lb
thermal efficiency
kwh heat
Cooling Pond
acres
Circulating Water
gal/min.
Makeup Water
gal/min.
dissolved solids
ppm
Bottom Ash and
fly Ash
lb
Liquid Wastes
lb suspended solids
lb phosphates
lb boron
lb chromate
Water Blowdown
gal/min.
lb dissolved solids
lb phosphates
lb zinc
lb chlorine
lb coal

[illegible] PONDS FOR WASTE HEAT REJECTION

[illegible]

6.4 Dry Cooling

In dry cooling, the waste heat from the power plant is rejected by heating a stream of ambient air circulated through a large heat exchanger. The heat is transported from the condenser to the heat exchanger by a separate circulating water system. This circulating water may be a closed loop, physically separated from the condensing steam by the condenser heat exchange surfaces. Alternatively, a direct contact spray condenser may be used, wherein a portion of the condensate flows to the boiler, while the remainder is pumped through the dry cooling tower and returns as spray to the condenser. In some designs the low pressure steam from the turbine is condensed directly on the air-cooled heat exchange surfaces, but this is probably not feasible for large power plants because of the enormous volumes of heat exchanger and piping associated with the low pressure steam.

Air is circulated through the dry cooling tower either by electrically driven blowers or by natural circulation through a large hyperbolic tower similar in design but much larger than the hyperbolic towers used in natural draft evaporative cooling towers.

Because it operates on the dry-bulb ambient air temperature, dry cooling is less efficient in energy utilization than evaporative cooling, which operates on the much lower wet-bulb temperature of the air. Consequently, the average temperature at which steam is condensed is higher for dry cooling, the steam condenses at a higher pressure, and less total work is obtained in expanding the steam through the turbine. Mechanical draft dry coolers also require substantial inputs of electrical power for the blowers. Consequently, dry cooling decreases the net thermal efficiency of the power plant and, for the same electrical output, results in larger quantities of make-up fuel, chemical and radiological effluents, and thermal discharges. Dry cooling towers are also more expensive in capital cost than evaporative cooling towers. Recent cost estimates in the range of $10/kw(e)(15) to $50/kw(e)(16) have been quoted.

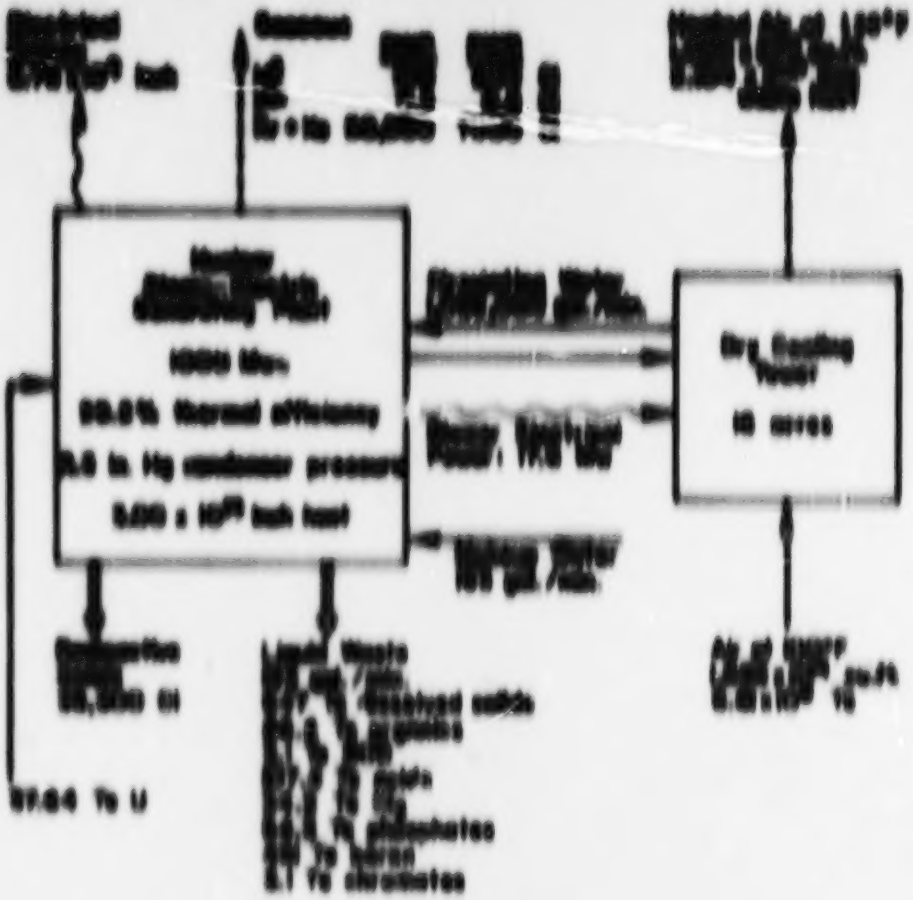
Balanced against these disadvantages is the very small water consumption for a dry cooled electrical power plant.

In a recent design(16) of a 800 Mw(e) power plant with dry cooling the total plant water requirement is specified as 80 gal/min for boiler feed make-up, bearing cooling, and fire protection. This is scaled here according to the total thermal power to yield estimated water make-up rates of 199 gal/min for a light-water nuclear plant and 104 gal/min for a coal-fired plant, each with dry cooling, as shown in the dry-cooling flowsheets Figures 6.7 and 6.8. This water make-up rate is, however, much smaller than that quoted by Rossi(15,17), where 30 gal/min per megawatt of electrical power was estimated. This must reflect differences in estimated water consumption for plant auxiliary services and leakage, since the actual blowdown water from the steam system of a 1000 Mw(e) nuclear plant is only about 10 gal/min(18).

Representative performance characteristics for mechanical-draft dry cooling towers for a light-water nuclear plant and for a fossil plant are presented in Table 6.2, calculated from data presented by Chave(18) on heat-transfer, blower power, and cost. For this analysis it is assumed that the temperature rise of the circulating coolant is 15°F and the

Figure 6.7

Light-Water Nuclear Plant, Waste-Heat Rejection by Dry Cooling


1000 MWe
33.0% thermal efficiency
3.5 in. Hg condenser pressure
Dry Cooling Tower
10 acres
Liquid Waste
dissolved solids
phosphates
boron
chromates

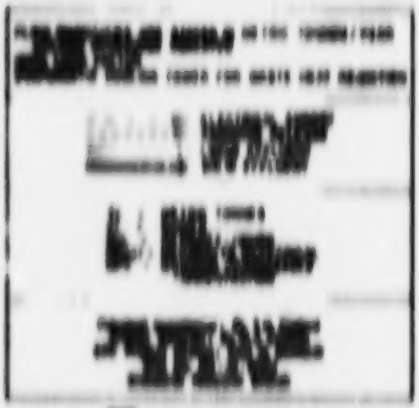


Figure 8.8

Coal-Fired Power Plant, Waste-Heat Rejection by Dry Cooling

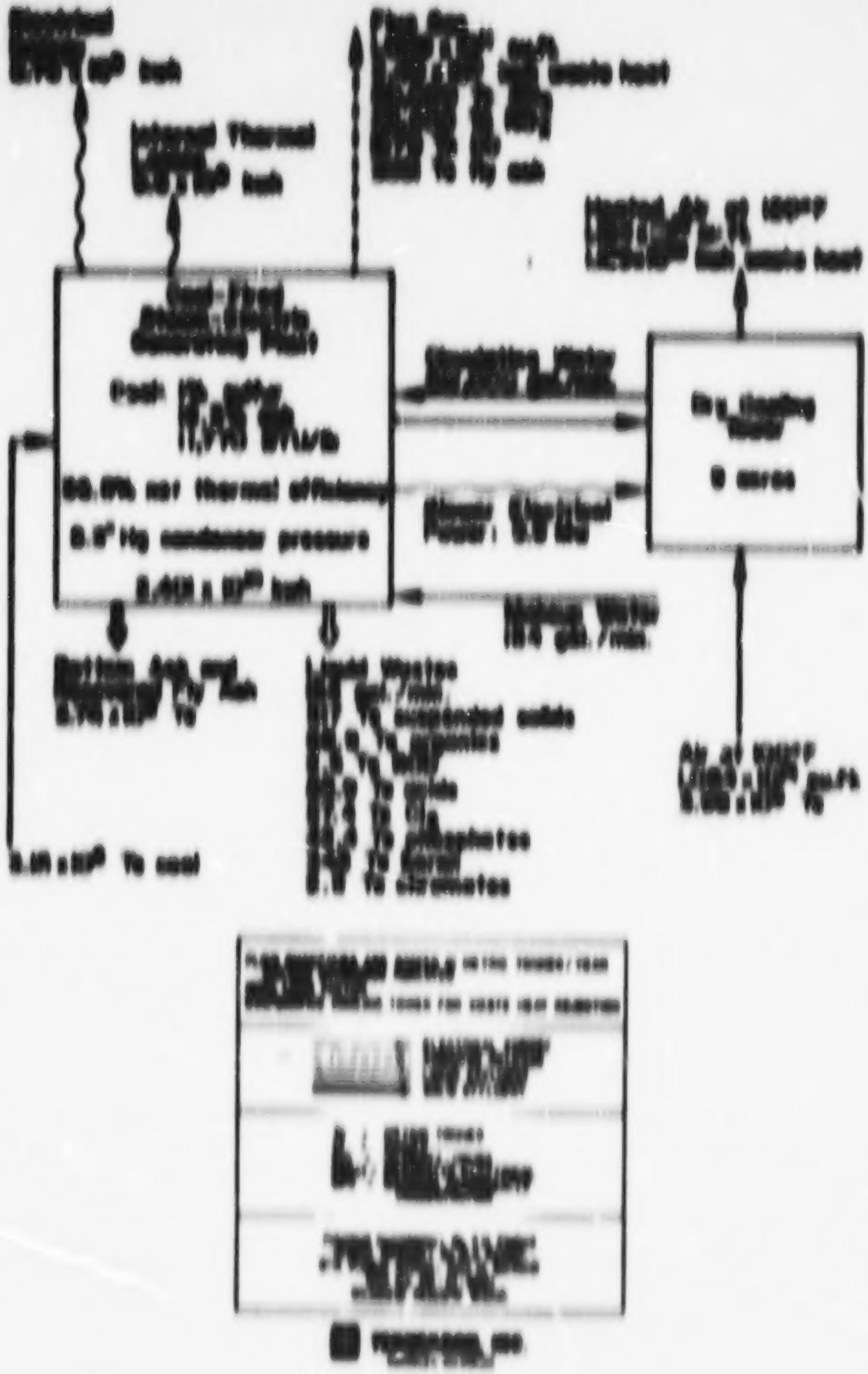

Electrical Energy
kwh
Internal Thermal Losses
kwh
Flue Gas
waste heat
Heated Air at 100°F
waste heat
Coal-Fired Steam-Electric Generating Plant
net thermal efficiency
Hg condenser pressure
kwh
Circulating Water
Dry Cooling Tower
acres
Blower Electrical Power
Makeup Water
gal./min.
Bottom Ash and
Liquid Wastes
suspended solids
phosphates
chromates
To coal
Air at
Teknekron, Inc.

Table 6.7

Heat Rejection by Forced Draft Dry Cooling

1000 Mw Net Electrical Output

	Nuclear (Water Reactors)			Fossil		
	Ambient Air Temperature, °F			Ambient Air Temperature, °F		
	60	80	100	60	80	100
Condenser back pressure, in. Hg	2.75	5.0	8.3	2.75	5	8.3
Total heat generation rate, Mw(t)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Condenser heat reject rate, Mw(t)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Blower power, Mw(t)	16.2	16.8	17.6	9.4	9.6	9.9
Condenser cooling water, 35°F temperature rise, gal/min.	[illegible]	1,205,000	1,205,000	[illegible]	[illegible]	[illegible]
Air circulation rate, 35°F temperature rise, cu.ft./min.	3.2×10^8	3.3×10^8	3.5×10^8	[illegible]	[illegible]	[illegible]
Capital cost of cooler, $\$10^6$	31	33	38	18.0	18.2	18.7
Land for coolers, acres	15.0	15.8	16.5	8.8	9.0	9.2
Fuel requirement relative to wet cooling at 1.5 in. Hg back pressure	1.02	1.05	1.09	1.01	1.02	1.05

temperature rise of the air is 30°F. Inlet air temperatures of 60, 80, and 100°F are considered. Listed in Table 6.1 are the blower power and the total heat generation rate to furnish the blower power, other plant energy loads, and a net electrical product of 1000 Mw(e). The increase in thermal power with increasing inlet air temperature is a result of the increasing condenser pressure. Because of the relatively low pressure of turbine-inlet steam in the light-water nuclear plant and because of the greater importance of expansion work in the low-pressure portion of the steam cycle, the nuclear plant is relatively sensitive to condenser pressure. As compared with once-through cooling or evaporative cooling with a low wet-bulb temperature, dry cooling with an inlet air temperature of 100°F results in a reduction of the net thermal efficiency from 32% to 29.2% and a 9% increase in make-up fuel requirement. Similarly, for the fossil plant, dry cooling with 100°F air reduces the net thermal efficiency from 38% to 36.5% and increases the fuel make-up requirement by 4%.

As a result of the very small amount of water discharged from a dry-cooled nuclear plant there is no medium to dilute the liquid radioactive discharges. The radioactive waste management system must then be capable of reducing the non-tritium radioactive liquid discharges to about 0.005 Ci/yr and the tritium liquid discharges to about 1.0 Ci/yr to meet the proposed Appendix I design-objective concentrations of 2×10^{-8} microcuries/cc for non-tritium radionuclides and 5×10^{-6} microcuries/cc for tritium in liquid effluents. There is technology available to accomplish these reductions. If the tritium is controlled by returning all tritiated water to the reactor coolant system, the tritium released yearly to the reactor coolant will eventually appear as gaseous tritium release[18], as is indicated on the flowsheet.

There is a compensating advantage resulting from the large volume of air passing through the cooling tower. If all the primary and secondary air sources containing gaseous radionuclides are discharged into the air stream leaving the cooling tower, the rapid mechanical dilution followed by atmospheric dispersion will result in far lower concentrations of airborne radionuclides at and beyond the site boundary. This may provide an alternative means of reducing the offsite concentration of gaseous radioiodine to the design-objective levels proposed in Appendix I of the 10 CFR 50 regulations, i.e., 10^{-15} microcuries/cc when milk-food chains are considered. (The possible problem of gaseous radioiodine effluents is discussed in Section 2.8).

The large volume of exhaust air from dry cooling towers may also be useful in aiding the dilution of flue gas effluents in fossil-fueled plants. The volume of dry-cooling tower air is about 1000 times greater than the volume of flue gas from a coal plant. Discharging the flue gas into the dry-cooling air would result in a thousand-fold dilution at the point of release, with further atmospheric dilution occurring as the mixed discharge air disperses through the environment. (The total mass emission of these effluents is, of course, not reduced by dilution.) Because the dry-cooling air is not humidified in the process of receiving the waste heat, the acid-rain problems discussed earlier for evaporative cooling, which can result from the oxidation and interaction of sulfur oxides with water vapor, would be expected to occur to a far less extent with dry-cooling air. In fact, because of the relatively high temperature of the mixed flue-gas air stream and the consequently higher vapor pressure of sulfuric and sulfurous acids, acid rain could conceivably be less of a problem with dry cooling than when the flue gas is discharged into the ambient air environment.

REFERENCES

1. Perry, J. H., Ed., Chemical Engineers' Handbook, 3rd ed., [illegible] pp., McGraw Hill (1950).

2. Detroit Edison Co., Final Environmental Impact Statement for the Fermi II Nuclear Power Plant.

3. Shofner, F. M. and C. O. Thomas, "Drift Measurements in Cooling Towers," Cooling Towers, Chemical Engineering Progress Technical Manual, A.I.Ch.E. (1972).

4. Mangelson, [illegible] A., "Ecological Aspects of Cooling Systems," Cooling Towers, Chemical Engineering Progress Technical Manual, A.I.Ch.E. (1972).

5. Holzworth, [illegible] and [illegible], "Legal Aspects of Salinity Caused by Cooling Towers," Cooling Towers, Chemical Engineering Progress Technical Manual, 64-68 A.I.Ch.E. (1972).

6. Hosler, [illegible], "Salt Water Cooling Tower," Cooling Towers, Chemical Engineering Progress Technical Manual, 115-117 A.I.Ch.E. (1972).

7. Pigeon, [illegible] and [illegible] Boyle, "How to Cool Steam-Electric Power Plants," Chemical Engineering Progress Technical Manual, 94-100 A.I.Ch.E. (1972).

8. Horst, M., "Evaluation of Cooling Tower Water Treatments," Cooling Towers, Chemical Engineering Progress Technical Manual, 70-76 A.I.Ch.E. (1972).

9. Griffin, [illegible], "Corrosion Control of Cooling Towers," Cooling Towers, Chemical Engineering Progress Technical Manual, 64-68 A.I.Ch.E. (1972).

10. Brooke, M., "Development of Cooling Water Treatment," Cooling Towers, Chemical Engineering Progress Technical Manual, 76-77 A.I.Ch.E. (1972).

11. Campbell, [illegible], "Supply, Use, and Disposal Problems," Cooling Towers, Chemical Engineering Progress Technical Manual, 78-82 A.I.Ch.E. (1972).

12. Hosler, C. L., "Wet Cooling Tower Plume Behavior," Cooling Towers, Chemical Engineering Progress Technical Manual, 27-32 A.I.Ch.E. (1972).

13. Jaske, R. T. and H. B. Orme, "Simulation of Evaporation from a Cooling Lake with a Comparison to a Real Case and the Alternative Use of Cooling Towers," Cooling Towers, Chemical Engineering Progress Technical Manual, 131-137 A.I.Ch.E. (1972).

14. Johnson, V. T., "A Conceptual Design for a Power Plant Dry-Cooling System Using a Hyperbolic Tower," Cooling Towers, Chemical Engineering Progress Technical Manual, A.I.Ch.E. (1972).

15. Rossie, J. P., "Dry-Type Cooling Systems," Cooling Towers, Chemical Engineering Progress Technical Manual, A.I.Ch.E. (1972).

16. Dynatech R/D Company, "A Survey of Alternate Methods for Cooling Condenser Discharge Water; Large Scale Heat Rejection Equipment," 16130 DHS (July, 1969).

17. Rott, G. R., "Dry Cooling Towers," Proc. American Power Conference, 1963.

18. Rodger, W. A., Testimony on Behalf of Consolidated Utility Group, U.S.A.E. United States Atomic Energy Commission Hearings on Proposed "As Low As Practicable" Amendment to 10 CFR 50 "Licensing of Production and Utilization Facilities," Docket RM 50-2 (April, 1972).

19. Chave, C. T., "Applicability of Air Cooling to Siting Problems in the Pacific Coast Area," Pacific Coast Electrical Association, Engineering and Operating Conference, San Francisco (March, 1970).

20. Parker, F. L. and P. A. Krenkel, "Thermal Pollution: Status of the Art," Report No. 3, Department of Env. and Water Resources Engineering, Vanderbilt University, Nashville, Tennessee (December, 1969).

21. Likens, G. E., F. H. Bormann, N. M. Johnson, "Acid Rain," Environment, 14, 33-40 (March, 1972).

7. ELECTRICAL POWER FROM LOW Btu GAS MADE FROM HIGH-SULFUR COAL

One of the many alternate processes for reducing sulfur dioxide effluents from high sulfur coal fuel involves the production of fuel gas from the coal and the chemical separation of sulfur before this gas is burned as fuel in an electrical generating plant. A representative fuel cycle for this process, beginning with coal shipped to the gasification process, is shown in Figure 7.1. The process considered here is based upon the design by Squires(1,2), whereby pulverized coal is gasified in a high-temperature ash-agglomerating fluidized bed fed with air and steam, producing a low-Btu (i.e. low heating value) fuel gas according to the overall water-gas reaction

$$C + H_2O \rightarrow CO + H_2$$

Heat for the endothermic reaction is supplied by oxidation of carbon by air on the lower part of the bed, locally forming CO_2 which then shifts to combustible CO in contact with carbon in the higher-temperature zones of the gasifier. Volatiles from the coal form hydrogen, methane, and higher hydrocarbons. Much of the coal ash agglomerates and is removed from the bottom of the gasifier for storage. Volatile sulfur compounds in the gasified product are H_2S and, to a lesser extent, COS(3). It is assumed that 0.01% of the gasifier product leaks to the atmosphere.

The crude power gas from the gasifier is cooled* to about 1400°F

---

*The heat extracted can be used to generate high-pressure steam for power conversion.

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

∿∿∿∿∿▶ ELECTRICAL ENERGY
- - - - - ▶ AIRBORNE RELEASE
═════▷ LIQUID EFFLUENT
━━━━━▶ SOLID EFFLUENT

Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSIBLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keeton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

TEKNEKRON, INC.
BERKELEY, CALIFORNIA

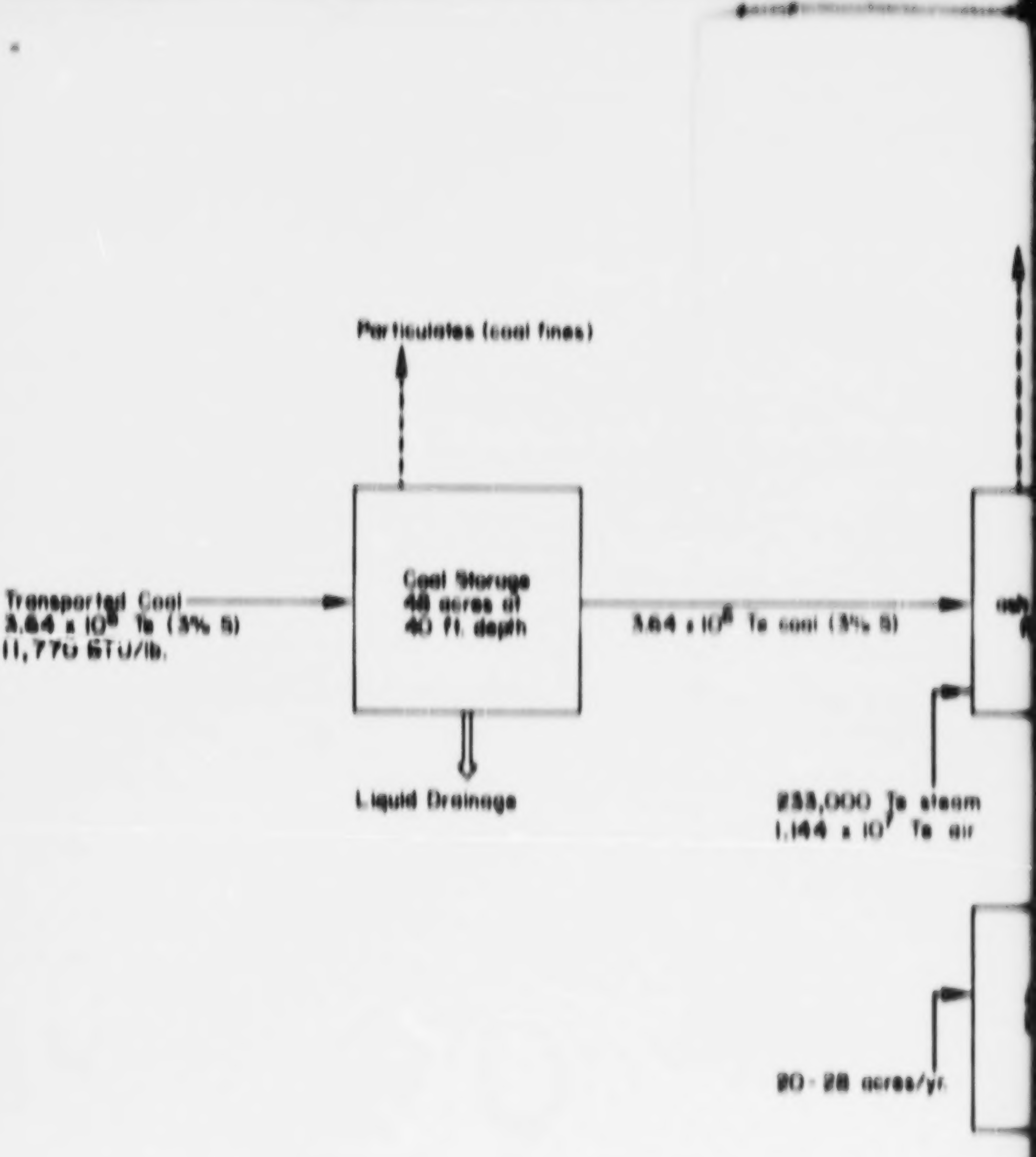
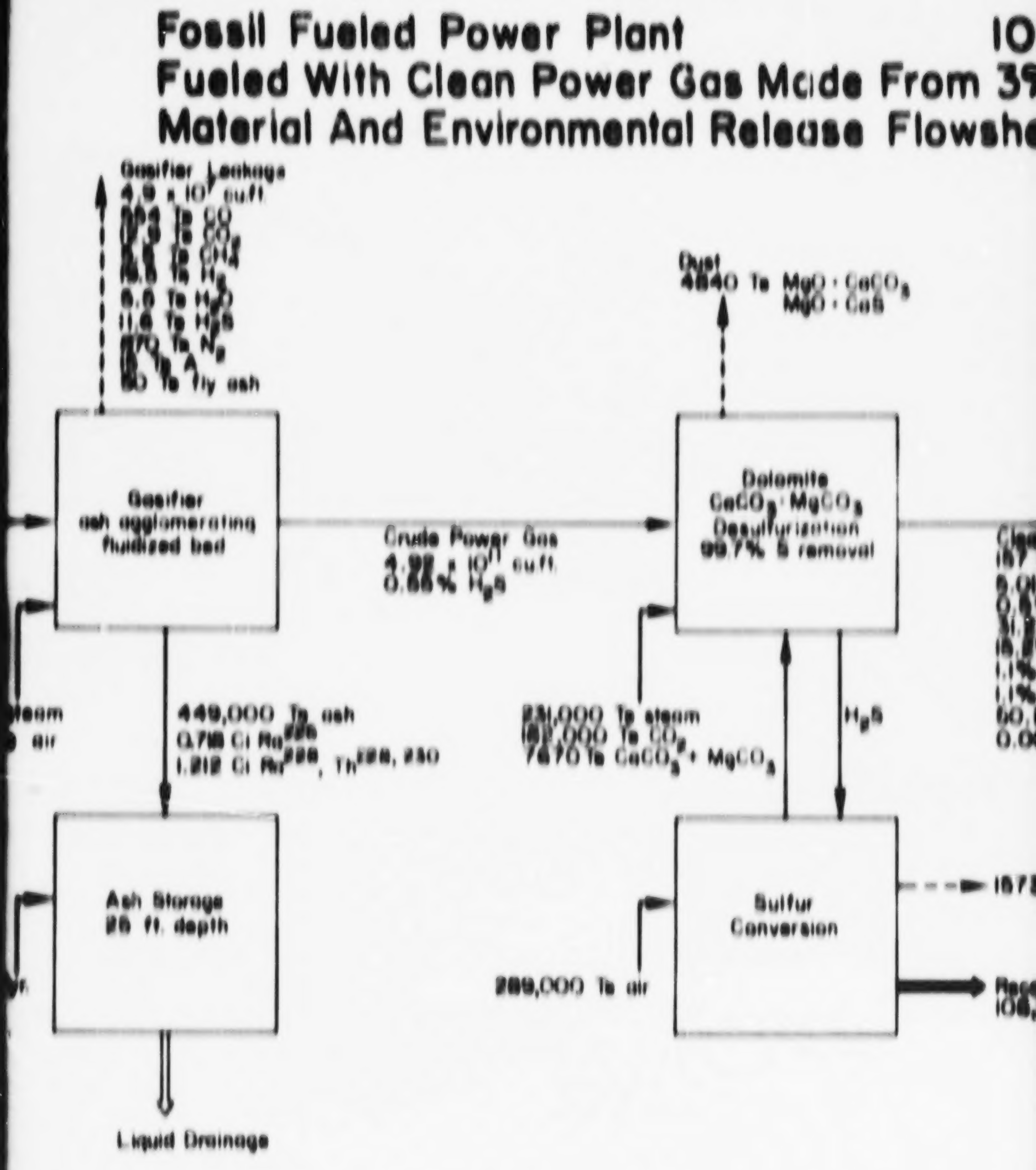

Particulates (coal fines)
Transported Coal
3.64×10^{6} Ts (3% S)
11,770 BTU/lb.
Coal Storage
48 acres of
40 ft. depth
3.64×10^{6} Ts coal (3% S)
Liquid Drainage
233,000 Ts steam
1.144×10^{7} Ts air
20 - 28 acres/yr.

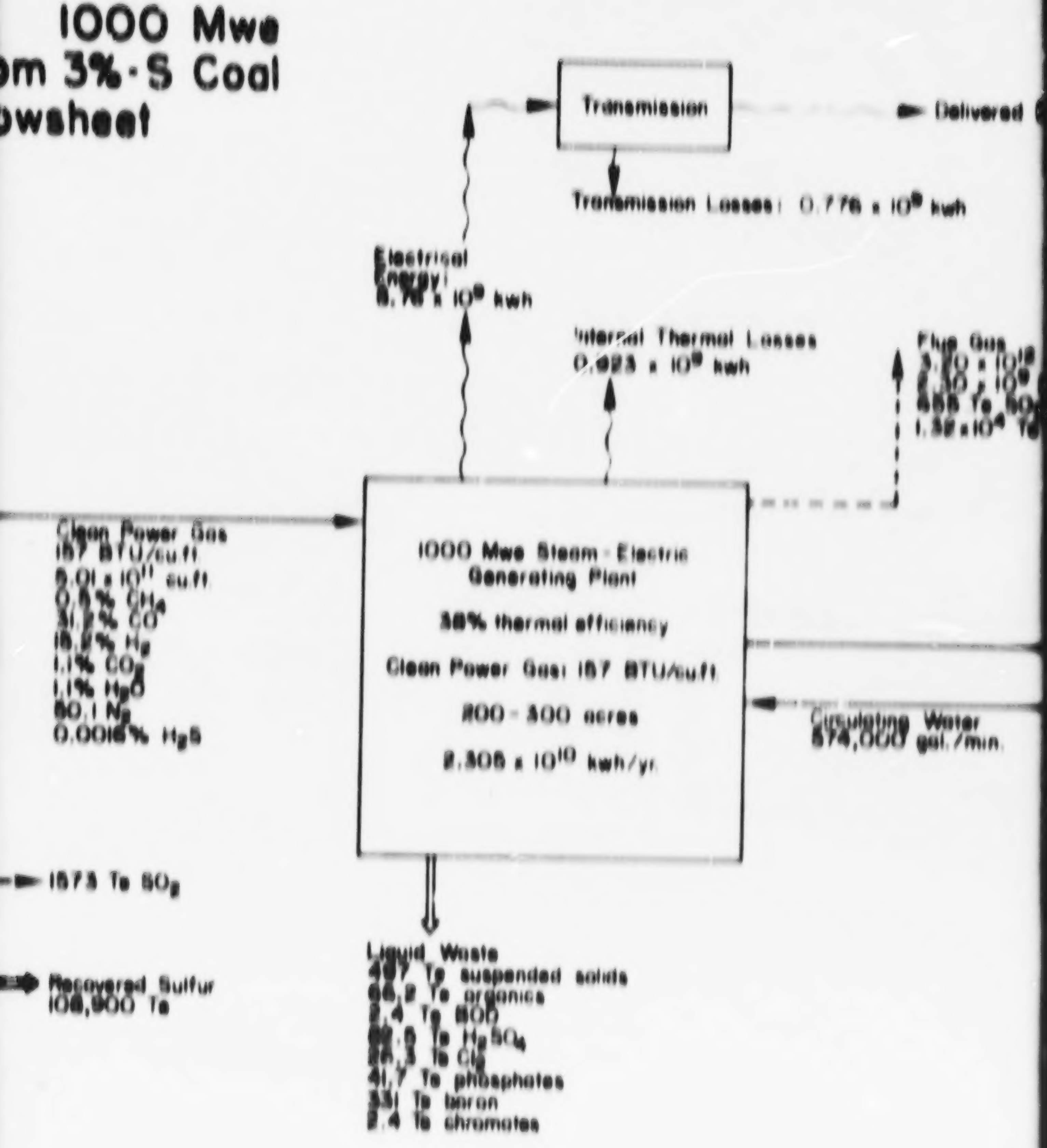
Figure 7.1

Fossil Fueled Power Plant IO
Fueled With Clean Power Gas Made From 39
Material And Environmental Release Flowshe

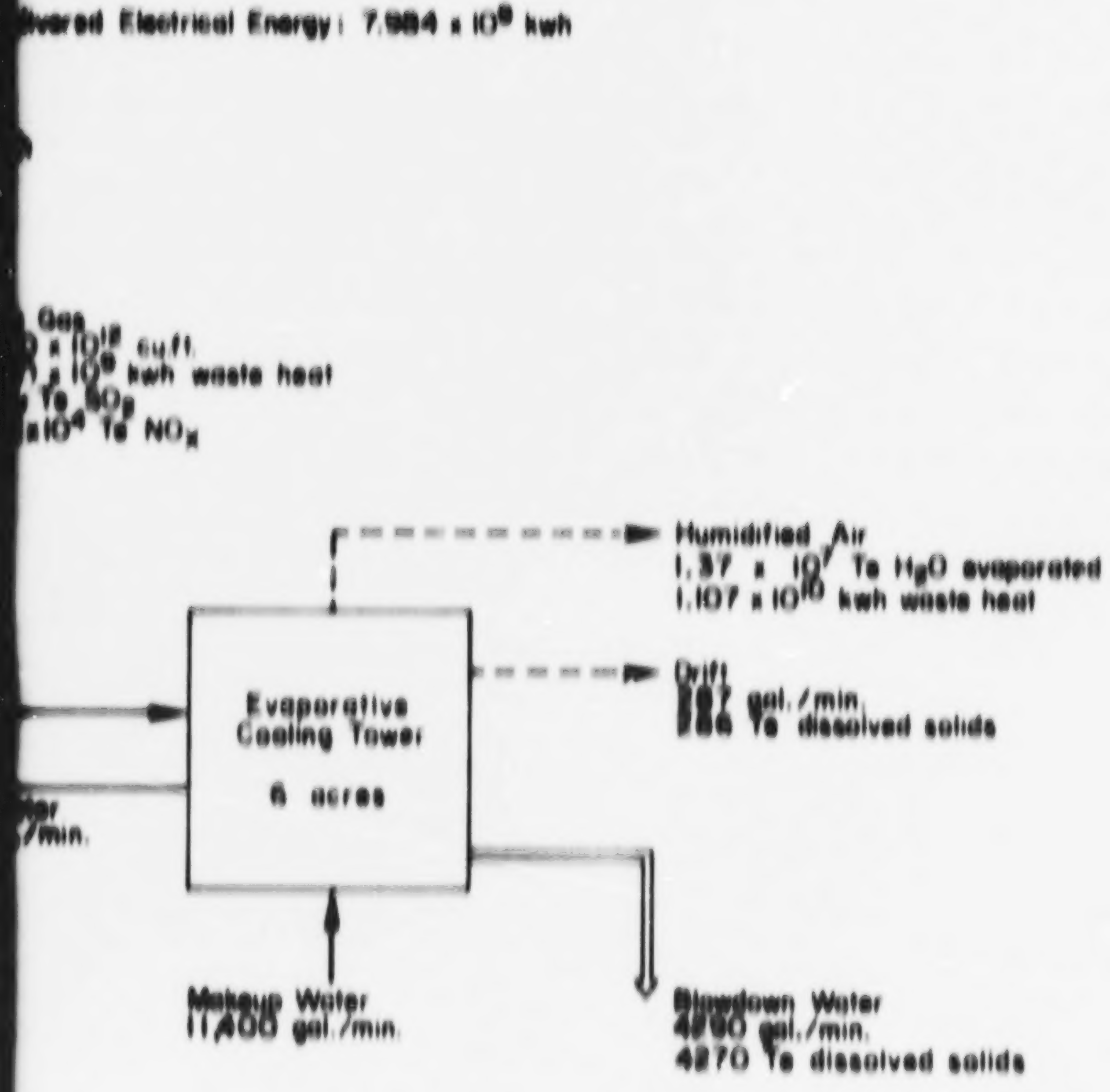


Gasifier Leakage
4.9 x 10^7 cu ft
Ts CO
Ts CO_2
Ts CH_4
Ts H_2
Ts H_2O
Ts H_2S
Ts N_2
Ts A
Ts fly ash
Dust
4840 Ts MgO : $CaCO_3$
MgO : CaS
Gasifier
ash agglomerating
fluidized bed
Crude Power Gas
4.92 x 10^11 cu ft
0.55% H_2S
Dolomite
$CaCO_3 \cdot MgCO_3$
Desulfurization
99.7% S removal
team
air
449,000 Ts ash
0.718 Ci Ra^{226}
1.212 Ci Ra^{228}, $Th^{228, 230}$
231,000 Ts steam
181,000 Ts CO_2
7670 Ts $CaCO_3$ + $MgCO_3$
H_2S
Ash Storage
25 ft. depth
Sulfur
Conversion
289,000 Ts air
Liquid Drainage

1000 Mwe
om 3%-S Coal
owsheet


Transmission
Delivered
Transmission Losses: 0.776 x 10⁹ kwh
Electrical Energy: 8.78 x 10⁹ kwh
Internal Thermal Losses 0.923 x 10⁹ kwh
Flue Gas
3.20 x 10¹²
2.30 x 10⁹
855 Te SO
1.32 x 10⁴ Te
Clean Power Gas
157 BTU/cu.ft.
5.01 x 10¹¹ cu.ft.
0.5% CH₄
31.2% CO
15.2% H₂
1.1% CO₂
1.1% H₂O
50.1 N₂
0.0016% H₂S
1000 Mwe Steam-Electric Generating Plant
38% thermal efficiency
Clean Power Gas: 157 BTU/cu.ft.
200-300 acres
2.305 x 10¹⁰ kwh/yr.
Circulating Water 574,000 gal./min.
1573 Te SO₂
Recovered Sulfur 108,900 Te
Liquid Waste
497 Te suspended solids
66.2 Te organics
2.4 Te BOD
82.5 Te H₂SO₄
26.3 Te Cl₂
41.7 Te phosphates
331 Te boron
2.4 Te chromates

C


livered Electrical Energy: 7.984 x 10⁹ kwh
Gas
x 10¹² cu.ft.
x 10⁹ kwh waste heat
Te SO₂
x10⁴ Te NOₓ
Humidified Air
1.37 x 10⁷ Te H₂O evaporated
1.107 x 10¹⁰ kwh waste heat
Drift
287 gal./min.
286 Te dissolved solids
Evaporative
Cooling Tower
6 acres
ter
/min.
Makeup Water
11,400 gal./min.
Blowdown Water
4990 gal./min.
4270 Te dissolved solids

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Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

and then flows into a gas desulfurization system, consisting of a panel bed filter charged with half calcined dolomite(2,4), $CaCO_3 \cdot MgO$. Gaseous H_2S reacts with the $CaCO_3 \cdot MgO$ to form a sulfurized solid on the filter, with an assumed sulfur removal efficiency of 99.75%[*] and an assumed 0.5% loss of dolomite.

Sulfurized solid from the panel bed filter is then reacted with steam and CO_2 at 1100°F to release gaseous H_2S and to regenerate the half-calcined dolomite for recycle to the panel bed(2). The heat evolved in regeneration and in the subsequent cooling of the H_2S-rich by-product gas can be used to generate additional high-pressure steam for power conversion. The CO_2 required for regeneration can be obtained from limestone calcination or can be recovered from the power-plant flue gas.

The gas rich in H_2S from sulfur desorption is converted to elemental sulfur for safe storage and for sale as a marketable by-product. The H_2S-rich gas is contacted at high pressure with aqueous H_2SO_3, yielding elemental sulfur according to the exothermic reaction(2),

$$H_2SO_{3(aq)} + 2H_2S_{(g)} \rightarrow 3S_{(l)} + 3H_2O$$

The H_2SO_3 solution is obtained by burning a portion of the sulfur product in air at high pressure and absorbing the resulting SO_2 gas in water(2). It is estimated that about 0.7% of the sulfur is lost to the atmosphere as SO_2 leakage(6). The separated liquid sulfur is cooled and solidified, and the remaining gaseous CO_2 and water vapor are recycled to the previous operation where the H_2S-rich gas was generated.

---

[*] Laboratory experiments(2) indicate sulfur removal of better than 99%, and dust removal of better than 99.9%.

The clean power gas consists mainly of combustible CO and H_2 and inert N_2. The heating value is estimated to be 167 Btu/cu.ft. (STP)[(2)]. Assuming that the coal contains 3% sulfur, the sulfur content of the gas is calculated to be 0.0018%.

It is assumed here that the coal gasification and gas cleaning process are located at the site of the electrical generating plant, to minimize the expense of transporting the low-heating value fuel gas. In this case overall savings in thermal efficiency for power generation can be obtained by taking advantage of the high temperature and high pressure of the product fuel gas, e.g., 1800°F and 14 atm., by burning the fuel gas with air, and expanding the hot high pressure combustion gases through a gas turbine, and then passing the hot turbine exhaust gas through a conventional steam boiler[(2,5)]. The gas turbine drives a compressor to furnish compressed air for combustion and for the gasifier and sulfur burner, and it also drives an electrical generator.

For the present flowsheet, which is to illustrate the material and environmental quantities resulting from application of the coal gasification technology to the basic steam-cycle for power conversion, the clean product gas is assumed to flow directly to a gas-fired boiler.

The present flowsheet is based upon one of the more advanced and efficient concepts for coal gasification and gas cleaning. According to the present calculations, about 20% more make-up coal is required for this fuel cycle (3.64 million Te/yr) than for the coal-fired power plant fuel cycle shown in Figure 3.1*. Assuming, for the purpose of comparison, that the properties of the make-up coal are the same for both fuel cycles except for the sulfur content, and assuming the same coal-treatment operations prior to gasification, the environmental and material quantities for the fuel cycle operations prior to gasification would be 20% greater than those listed in Figure 3.1.

---

*For the more advanced concept involving a combined gas-turbine steam-turbine energy conversion cycle coupled to the gasification process, 46% of the thermal energy available in the coal fed to the gasifier appears as electrical output from the plant(9). This would require about 30% less make-up coal than shown in Figure 3.1.

REFERENCES

1. Squires, A. M., "Clean Power Gas from Dirty Fuels," *Scientific American*, 227, No. 4, 26-35 (October, 1972).

2. Dobner, S., M. J. Gluckman and A. M. Squires, *Production of Low-Btu Gas from Coal in Combination with Advanced Power Cycles*, Paper No. [illegible], A.I.Ch.E. Annual Meeting (November 26-30, 1972).

3. Hottel, H. C. and J. B. Howard, *New Energy Technology, Some Facts and Assessments*, 144-167, M.I.T. Press (1971).

4. Ruth, L. A., A. M. Squires, R. A. Graff, "Desulfurization of Fuels with Half-Calcined Dolomite: First Kinetic Data," *Environmental Science and Technology*, 6, 1009 (1972).

5. Robson, F. L., A. J. Giramonti, G. P. Lewis and G. Gruber, "Technological and Economic Feasibility of Advanced Power Cycles and Methods for Producing Nonpolluting Fuels for Utility Power Systems," United Aircraft Research Laboratories Report for National Air Pollution Control Administration, U. S. Department of Health, Education and Welfare (December, 1970).

6. Squires, A. M., "Clean Power from Coal," *Science 169*, No. 3948, pp. 821-828.

7. Squires, A. M., *The Coalplex: Gas, Gasoline, and Clean Electricity from Coal*, Paper No. [illegible], A.I.Ch.E. Annual Meeting (November 26-30, 1972).

8. Grossman, P. R. and R. W. Curtis, "Pulverized-Coal-Fired Gasifier for Production of Carbon Monoxide and Hydrogen," *Trans. ASME*, 76, 689-695 (1954).

9. Chopey, N. P., "Coal Gasification: Can It Stage a Comeback?", *Chemical Engineering*, 44-46 (April 3, 1972).

8. ELECTRICAL POWER FROM HIGH-SULFUR COAL, SO_2 REMOVAL BY WET LIMESTONE SCRUBBING

8.1 Process Description

The wet-limestone scrubbing process is designed to remove 90% of the sulfur which would otherwise appear in the stack-gas effluent when burning high-sulfur coal. A representative fuel cycle for this process, beginning with coal shipped to the electrical generating plant, is shown in Figure 8.1. Finely ground limestone ($CaCO_3$) or dolomite ($CaCO_3 \cdot MgCO_3$) is injected into the furnace, or into the hot flue gas, of a power plant fueled with high-sulfur coal. Thermal energy is consumed in decomposing the limestone, according to the reaction

$$CaCO_3 \rightarrow CaO + CO_2$$

About 20%(1,2) of the sulfur dioxide formed in coal combustion reacts with the solid CaO according to the reaction

$$CaO + SO_2 + 1/2\ O_2 \rightarrow CaSO_4$$

and is removed from the flue gas. The remaining SO_2 and the suspended calcined solids flow with the flue gas and fly ash into a scrubbing tower, where the gases are contacted counter-currently with a recirculating liquid solution and slurry of hydrated calcium oxide and calcium sulfate.

Sulfur dioxide in the gas absorbs and reacts with hydroxyl and bicarbonate ions to form HSO_3^- and $SO_3^=$ ions. These ultimately oxidize to the more stable $SO_4^=$ ions and precipitate as $CaSO_4$. The scrubber is also expected to remove fly ash from the flue gas, eliminating the need for an electrostatic precipitator.

A purge stream of slurry from the scrubbing circuit flows to a settling pond where the solid $CaSO_4$, $Ca(OH)_2$, $CaCO_3$, and fly ash are removed and stored. Settling pond overflow is recycled and make-up process water is added to the system to compensate for the evaporation loss in the settling pond and in the scrubbing tower.

8.2 Basis for Flowsheet Quantities

It is assumed for the purpose of comparison that coal fuel is identical in origin and characteristics with that considered in Chapter 2, except that the sulfur content has been increased from 1% to 3%. The quantity of transported coal includes 3.03 x 10^6 Te/yr for the basic coal plant of 38% thermal efficiency plus 240,000 Te/yr to calcine the $CaCO_3$ injected into the boiler$^{(1)}$, for a total of 3.47 x 10^6 Te/yr. The net overall thermal efficiency is then 35.5%. Environmental releases in coal mining, coal cleaning and processing are those indicated on the basic coal-plant flowsheet (Figure 3.1), multiplied by 1.14 to allow for the increased coal consumption due to limestone injection.

The amount of limestone injected is calculated on the basis of 110% of the amount stoichiometrically needed to react with all the sulfur in the coal$^{(1)}$. The amount of wet limestone (91.8% $CaCO_3$) is 8.95

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

〜〜〜〜→ ELECTRICAL ENERGY
- - - - - → AIRBORNE RELEASE
⇒ LIQUID EFFLUENT
➡ SOLID EFFLUENT

Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
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EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

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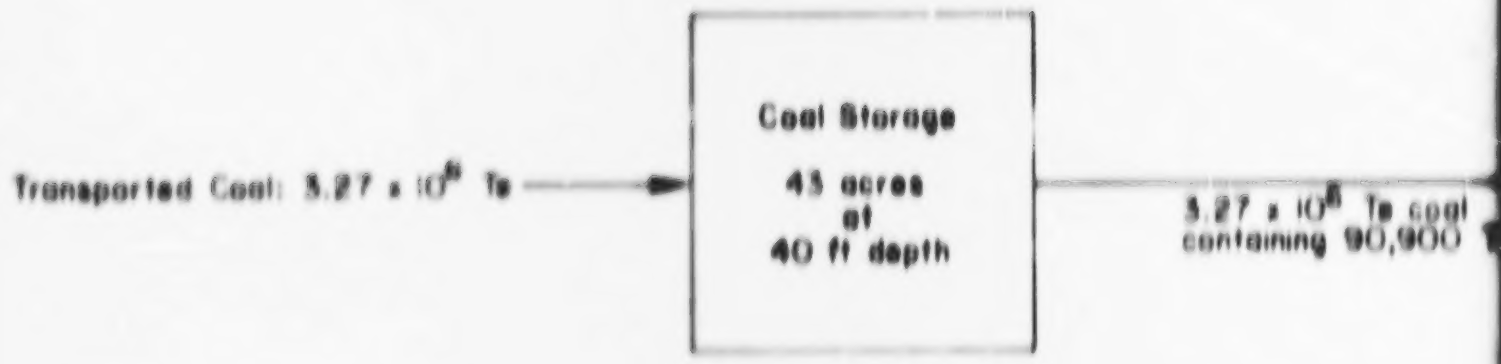
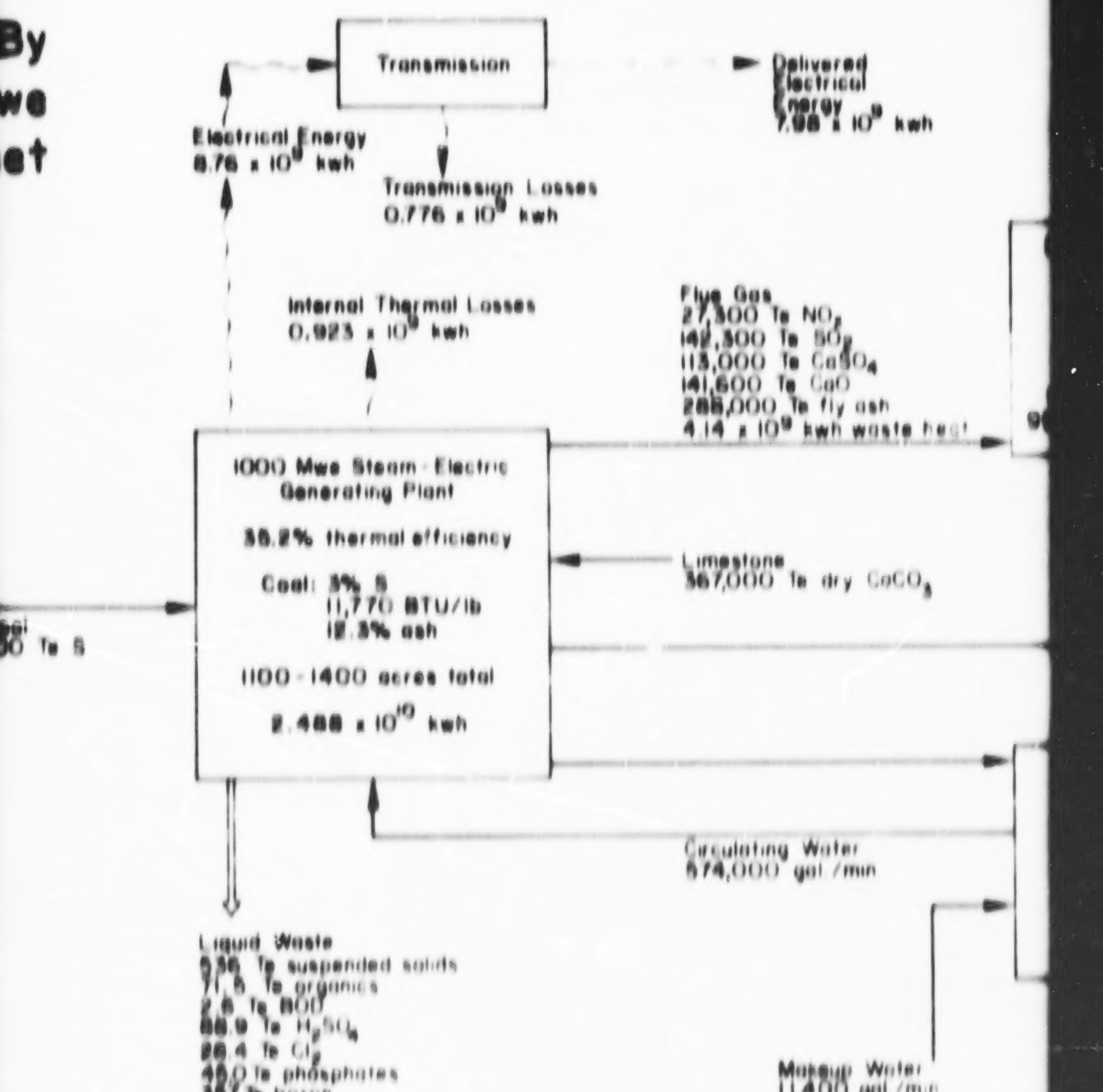
Figure 8.1

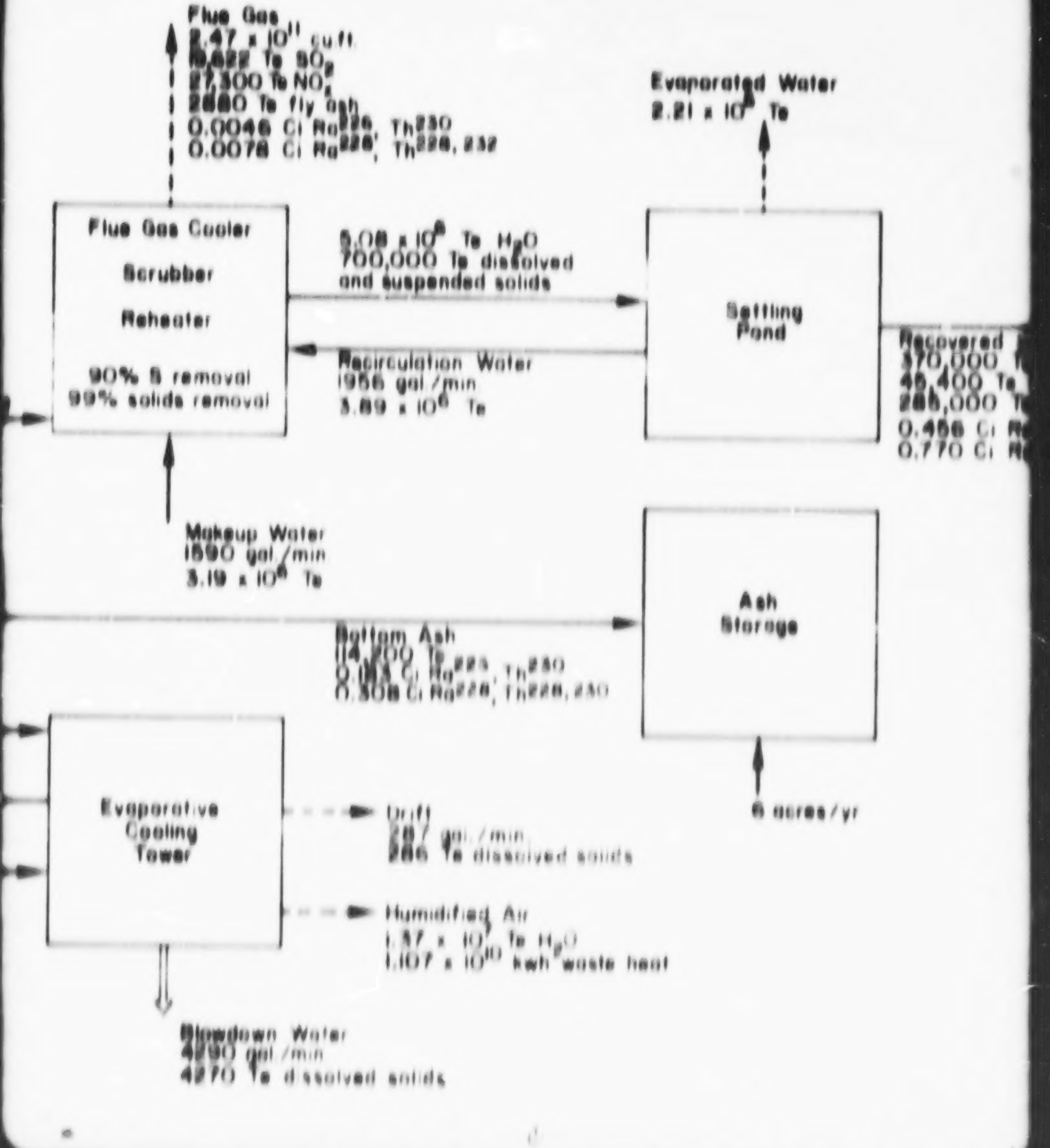
Coal Fired Power Plant - SO_2 Removal By Wet Limestone Scrubbing - 1000 Mwe Material And Environmental Release Flowsheet

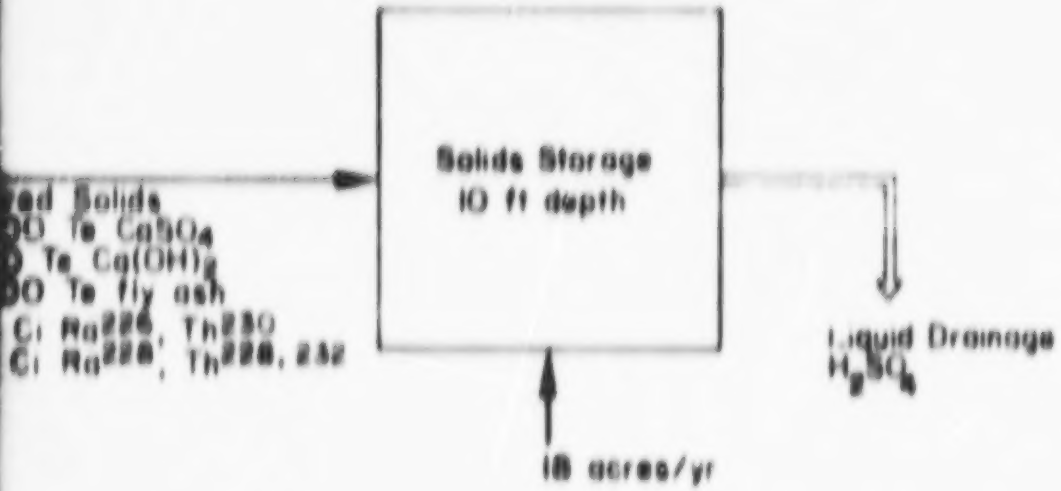


Transported Coal: 3.27×10^6 Te
Coal Storage
45 acres
at
40 ft depth
3.27×10^6 Te coal
containing 90,900

By
we
et


Transmission
Delivered Electrical Energy 7.98 x 10^9 kwh
Electrical Energy 8.76 x 10^9 kwh
Transmission Losses 0.776 x 10^9 kwh
Internal Thermal Losses 0.923 x 10^9 kwh
Flue Gas
27,300 Te NO$_x$
142,300 Te SO$_2$
113,000 Te CaSO$_4$
141,600 Te CaO
285,000 Te fly ash
4.14 x 10^9 kwh waste heat
1000 Mwe Steam-Electric Generating Plant
35.2% thermal efficiency
Coal: 3% S
11,770 BTU/lb
12.3% ash
1100-1400 acres total
2.488 x 10^{10} kwh
Limestone 367,000 Te dry CaCO$_3$
sel
00 Te S
Circulating Water 574,000 gal/min
Liquid Waste
536 Te suspended solids
71.5 Te organics
2.6 Te BOD
88.9 Te H$_2$SO$_4$
26.4 Te Cl$_2$
45.0 Te phosphates
357 Te boron
2.6 Te chromates
Makeup Water 11400 gal/min


Flue Gas
2.47 x 10^11 cu ft
19,622 Te SO2
27,300 Te NOx
2880 Te fly ash
0.0046 Ci Ra226, Th230
0.0078 Ci Ra228, Th228, 232
Evaporated Water
2.21 x 10^6 Te
Flue Gas Cooler
Scrubber
Reheater
90% S removal
99% solids removal
5.08 x 10^6 Te H2O
700,000 Te dissolved
and suspended solids
Settling Pond
Recirculation Water
1956 gal/min
3.89 x 10^6 Te
Recovered
370,000
46,400 Te
286,000
0.456 Ci
0.770 Ci
Makeup Water
1590 gal/min
3.19 x 10^6 Te
Ash Storage
Bottom Ash
114,200 Te
0.183 Ci Ra226, Th230
0.308 Ci Ra228, Th228, 232
6 acres/yr
Evaporative Cooling Tower
Drift
287 gal/min
286 Te dissolved solids
Humidified Air
1.57 x 10^7 Te H2O
1.107 x 10^10 kwh waste heat
Blowdown Water
4290 gal/min
4270 Te dissolved solids


Solids Storage
10 ft depth
ed Solids
00 Te $CaSO_4$
0 Te $Ca(OH)_2$
00 Te fly ash
Ci Ra^{226}, Th^{230}
Ci Ra^{228}, $Th^{228, 232}$
Liquid Drainage
H_2SO_4
18 acres/yr

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Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

greater. On-site storage of make-up limestone should be sufficient for at least a one-week supply. On-site wet-grinding and pulverizing is required and handling the limestone contributes to a dusting problem. It is assumed that all of the raw limestone is calcined to CaO in the boiler and 25% of the CaO is converted to $CaSO_4$ in the boiler(1). All of the sulfur originally present in the coal is assumed to evolve in the flue gas, either as suspended $CaSO_4$ or as SO_2.

Sulfur recovery of 90% in the scrubber is based upon the Kellogg flowsheet(1). Recovery may be limited by the partial pressure of SO_2 above locally acidic scrubbing liquid containing dissolved H_2SO_3. A scrubbing-removal efficiency of 99% for the fly ash is based upon the Kellogg analysis(1). With this efficiency no electrostatic precipetor for fly ash recovery is required.

The gas entering the scrubber is cooled to 177°F. The gas leaving the scrubber is reheated to 250°F to minimize acidic condensation and corrosion in the exhaust system(1).

The settling pond may serve as the storage area for the large amounts of solid wastes in the liquor extract leaving the scrubber. The slurry must be discharged to new settling areas as the ponds fill, or the settled solids can be recovered and piled for separate storage. The required settling-storage area is about 182 acre-feet per year(1). Groundwater contamination by acidic leach water can be a problem with the settling pond and storage of separated solids. If the limestone used for injection into the boiler is dolomite, the contained magnesium will follow the calcium in the process and will appear in the recovered solids. Since

$MgSO_4$ is more soluble than $CaSO_4$, it will more readily enter the ground water and surface-leach water. Settling ponds and storage areas may require some impermeable structure to avoid environmental contamination.

Environmental releases involved in waste heat rejection and liquid releases for plant operation are identical to those identified for the basic coal-plant flowsheet (Figure 3.1).

Wet limestone scrubbing with boiler injection of ground limestone has been demonstrated in two commercial plants of 125 and 140 Mw(e) capacity(1).

REFERENCES

1. M. W. Kellogg Co., *Evaluation of SO_2 Control Processes*, Task No. 5, Final Report, PB204711, EPA Contract No. CPA 70-68 (October, 1971).

2. M. W. Kellogg Co., *Detailed Cost Breakdown for Selected Sulfur Oxide Control Processes*, Task No. 9, Final Report, [illegible], EPA Contract No. CPA 70-68 (March, 1972).

3. Tennessee Valley Authority, *Sulfur Oxide Removal from Power Plant Stack Gas–Use of Limestone in Wet Scrubbing Process*, TVA Conceptual Design Study (1969) Final Report, Contract No. TV-29233A.

4. Pollock, W. A., J. P. Tomany, and G. Frieling, Mech. Eng. 89 (8), 21 (1967).

5. Radian Corp., *A Theoretical Description of the Limestone Injection Wet Scrubbing Process*, Final Report on Contract No. CPA 22-69-138, Vol. I (June, 1970).

6. Battelle Memorial Institute, *Investigation of the Limestone-SO_2 Wet Scrubbing Process*, Final Report, Contract No. PH86-68-84, Task Order No. 17 (November, 1969).

7. Tennessee Valley Authority, *Sulfur Oxide Removal from Power Plant Stack Gas: Sorption by Limestone or Lime–Dry Process*, Conceptual Design Study (1968).

9. ELECTRICAL POWER FROM GEOTHERMAL STEAM

9.1 Introduction

The fuel cycle flowsheet for the generation of 1000 Mw(e) from geothermal steam energy sources, shown in Figure 9.1, is based upon the technology used at the Geysers Geothermal Project of the Pacific Gas and Electric Company in Sonoma County, California. Low pressure steam, typically at 114 psig and 355°F, is extracted and piped from several nearby geothermal wells and flows into a low-pressure turbine for power generation. The expended steam is condensed by direct contact with water from an evaporative cooling tower. About 84% of the condensed steam serves as make-up water for the evaporative cooling system, and the remaining 16% of the condensate is returned as blowdown water to separate injection wells in the geothermal field. Evidently there is sufficient underground water supply to meet the water requirements for steam production.

The electrical capacity of each generating unit and its associated steam-supply wells is limited by the physical arrangement of steam piping. The present conceptual design of the 1000 Mw(e) facility consists of ten generating units, each with a capability of 100 Mw(e). Operating data on 55 Mw(e) units are available, and new units in the range of 100 Mw(e) are planned for the Geysers field(1). On the basis of these data, the overall plant efficiency of the 1000 Mw(e) conceptual design is 15.7%, requiring 7.25×10^7 Te/yr of geothermal steam to deliver 8.76×10^9 kwh of electrical product at 100% load factor.

FLOW QUANTITIES ARE STATED IN METRIC TONNES / YEAR UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

⇝ ELECTRICAL ENERGY
⇢ AIRBORNE RELEASE
⇨ LIQUID EFFLUENT
➡ SOLID EFFLUENT

Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68 - 01 0561
Standards Research Branch

TEKNEKRON, INC.
BERKELEY, CALIFORNIA

Geothermal
Material And

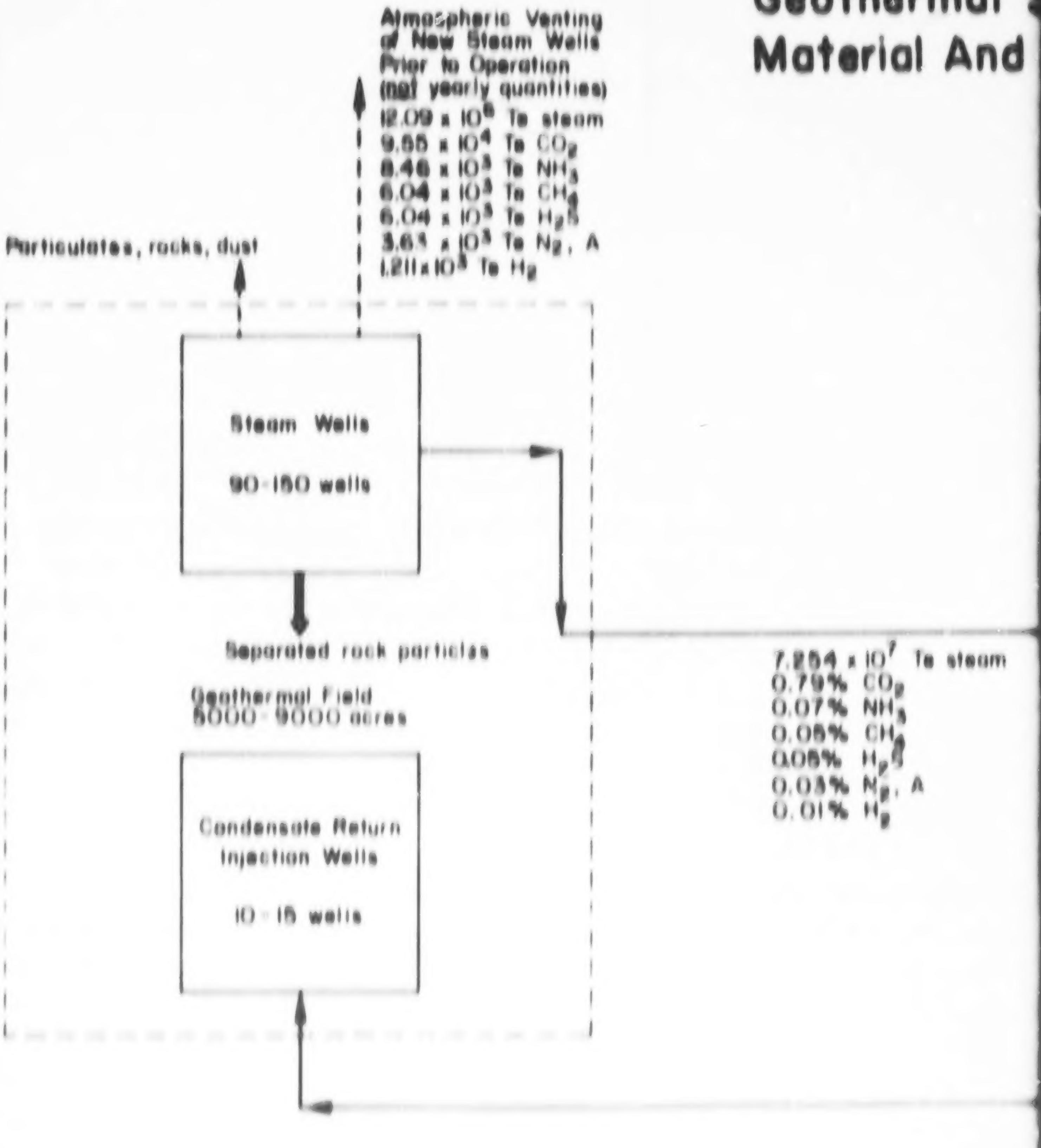
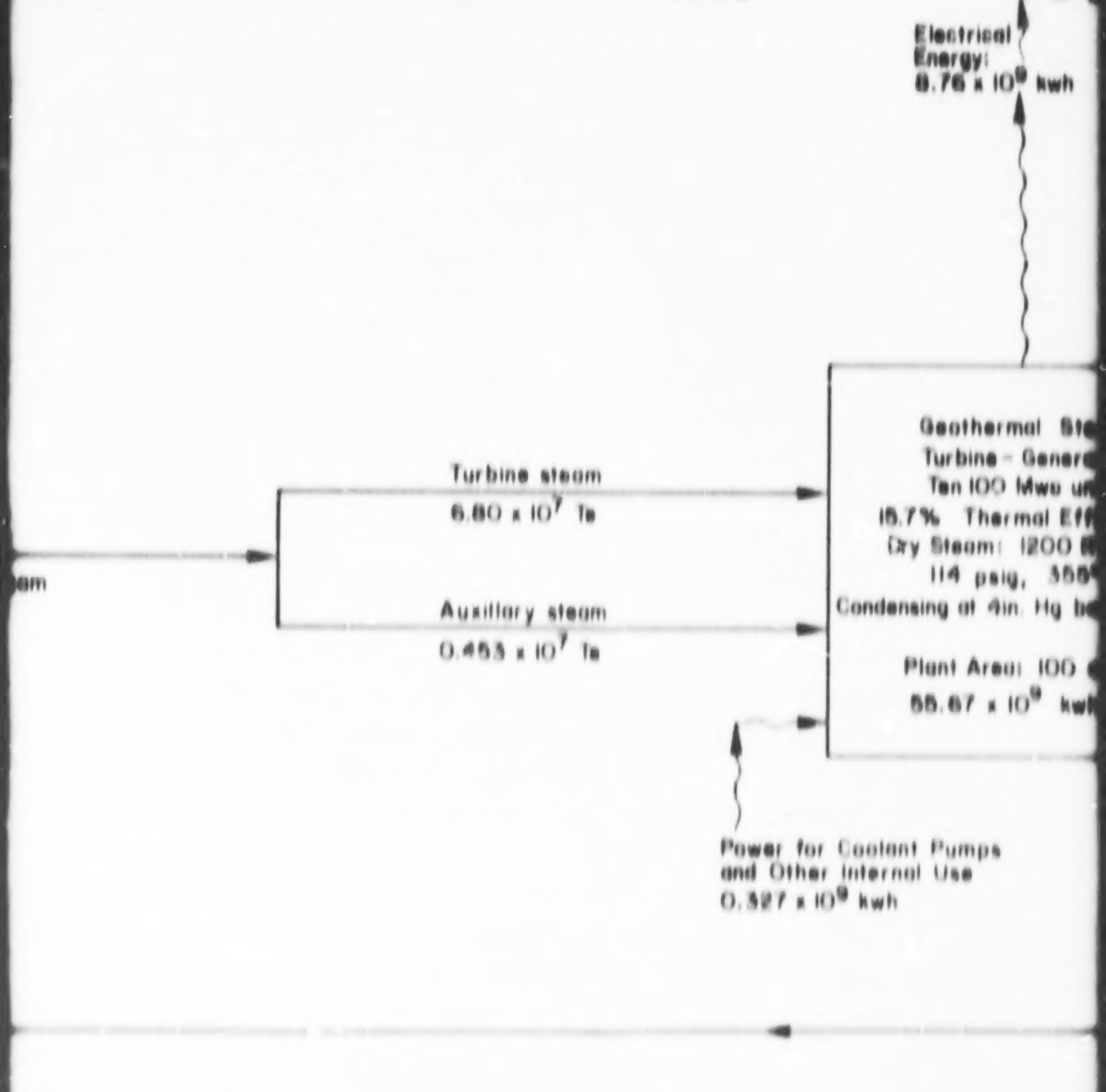
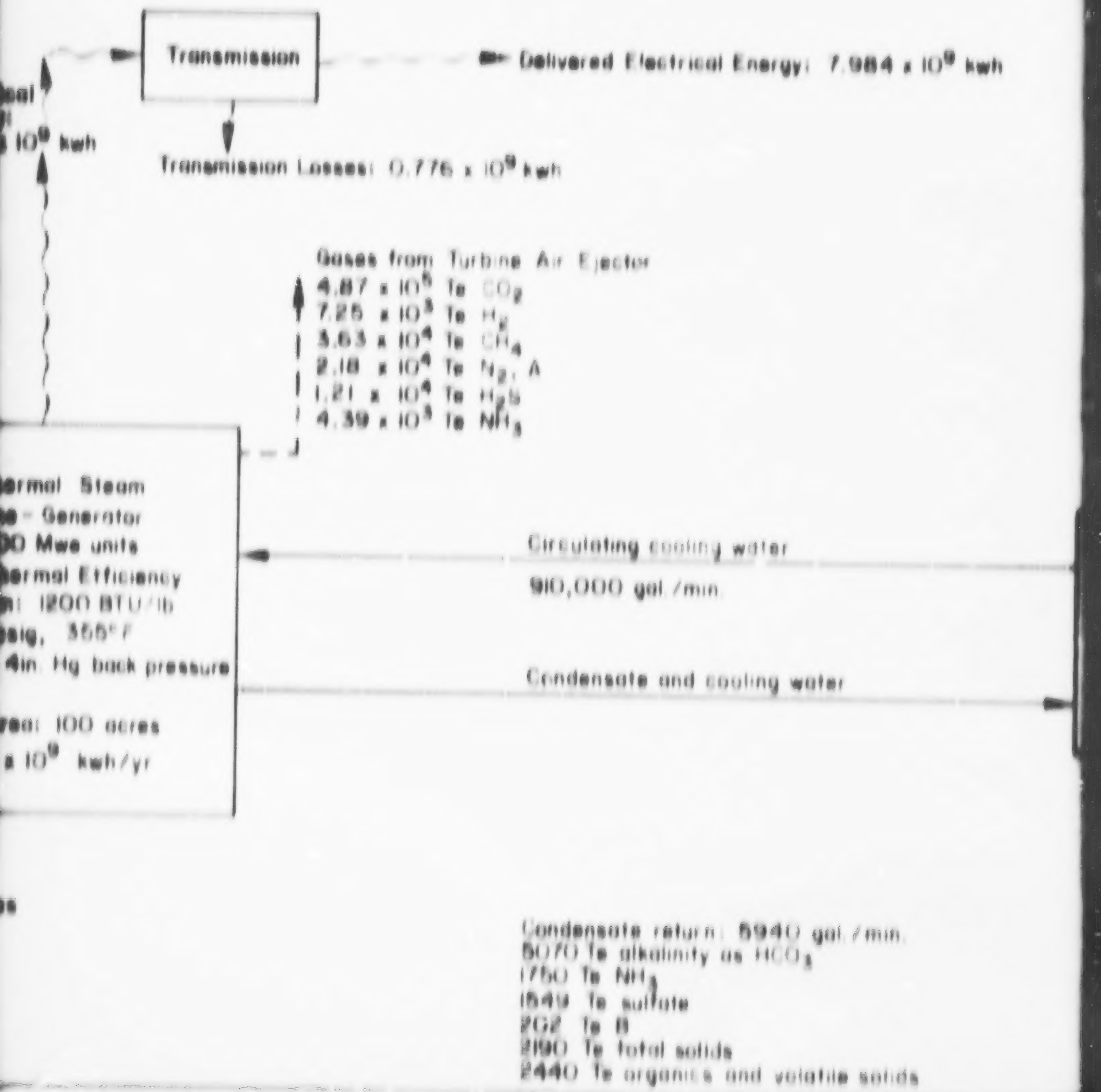
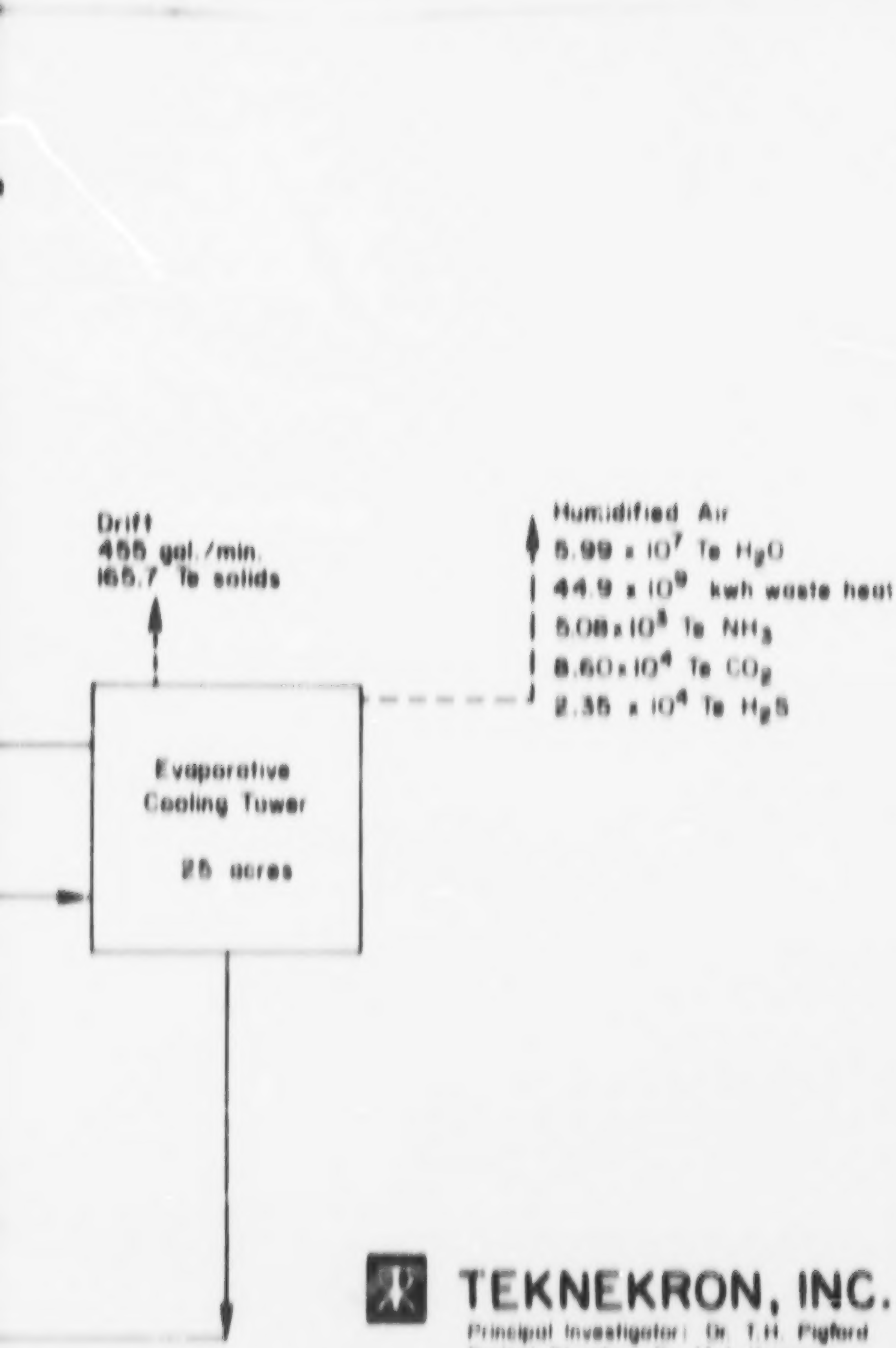

Atmospheric Venting
of New Steam Wells
Prior to Operation
(not yearly quantities)
12.09 x 10^6 Te steam
9.55 x 10^4 Te CO2
8.46 x 10^3 Te NH3
6.04 x 10^3 Te CH4
6.04 x 10^3 Te H2S
3.63 x 10^3 Te N2, A
1.211x10^3 Te H2
Particulates, rocks, dust
Steam Wells
90-150 wells
Separated rock particles
Geothermal Field
5000-9000 acres
Condensate Return
Injection Wells
10-15 wells
7.254 x 10^7 Te steam
0.79% CO2
0.07% NH3
0.05% CH4
0.05% H2S
0.03% N2, A
0.01% H2

Figure 9.1

al Steam Power Plant 1000 Mwe
nd Environmental Release Flowsheet


Electrical
Energy:
8.76 x 10⁹ kwh
Geothermal Ste
Turbine - Genera
Ten 100 Mwe un
15.7% Thermal Eff
Dry Steam: 1200 B
114 psig, 355
Condensing at 4in. Hg ba
Plant Area: 100
55.67 x 10⁹ kwh
Turbine steam
6.80 x 10⁷ lb
Auxiliary steam
0.453 x 10⁷ lb
am
Power for Coolant Pumps
and Other Internal Use
0.327 x 10⁹ kwh


Transmission
Delivered Electrical Energy: 7.984×10^9 kwh
Transmission Losses: 0.776×10^9 kwh
ical
10^9 kwh
Gases from Turbine Air Ejector
4.87×10^5 Te CO_2
7.25×10^3 Te H_2
3.63×10^4 Te CH_4
2.18×10^4 Te N_2, A
1.21×10^4 Te H_2S
4.39×10^3 Te NH_3
ermal Steam
e - Generator
00 Mwe units
hermal Efficiency
n: 1200 BTU/lb
sig, 355°F
4in. Hg back pressure
rea: 100 acres
$\times 10^9$ kwh/yr
Circulating cooling water
910,000 gal./min.
Condensate and cooling water
s
Condensate return: 5940 gal./min.
5070 Te alkalinity as HCO_3
1750 Te NH_3
1549 Te sulfate
262 Te B
2190 Te total solids
2440 Te organics and volatile solids


Drift
455 gal./min.
165.7 Te solids
Humidified Air
5.99×10^7 Te H_2O
44.9×10^9 kwh waste heat
5.08×10^5 Te NH_3
8.60×10^4 Te CO_2
2.35×10^4 Te H_2S
Evaporative
Cooling Tower
25 acres

TEKNEKRON, INC.
Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

The geothermal steam from the wells carries with it several pollutants, including CO_2, NH_3, CH_4, H_2S, and boron compounds, along with N_2, A, H_2, dust, and gravel. A typical steam analysis is shown in Table 9.1. The solids and particulates are separated before the steam enters the turbine. The more volatile species are emitted with the steam-ejector air vented from the condenser, others are emitted to the air flowing through the evaporative cooling tower, and the less volatile species are returned to the geothermal field via the injection wells.

Table 9.1

Typical Composition of Geothermal Steam(1)

	weight percent
CO_2	0.79
NH_3	0.07
CH_4	0.05
H_2S	0.05
N_2, A	0.03
H_2	0.01

Geothermal energy-conversion fuel cycles can be expected to differ significantly at different locations. For example, in some areas of the country with geothermal potential, such as Southern California, the geothermal wells produce hot brine instead of steam. Energy conversion would involve flashing the brine to steam or heat transfer to volatilize a working fluid, such as low-boiling organic, which expands through a turbine and is then condensed and recycled. The material and environmental fuel cycle parameters could be quite different from those shown in the present flowsheet.

9.2 Geothermal Steam-Extraction Wells

The wells supplying a single turbine-generator unit are generally located in the land area surrounding each generating unit. The entire Geysers development is comprised of a number of such adjacent areas in the geothermal field.

There is considerable variation in the steam production capability of each well. A 1972 report by Finney$^{(1)}$ indicates about 200,000 lb/hr of steam from a well typical of the newer development. To furnish the annual steam requirement of 7.25×10^7 Te/yr for the 1000 Mw(e) conceptual design, about 91 such wells would be required. However, in the existing field, about 6 to 8 wells of earlier vintage supply steam for the 55 Mw(e) unit, and this scales to about 150 wells for the present flowsheet.

The land area associated with the wells fueling the 55 Mw(e) unit at Geysers averages about 58 acres per well. This scales to about 5000 to 9000 acres for the 90 to 150 steam-producing wells estimated for the 1000 Mw(e) installation.

When a new well is to be brought into production it is first proved by venting to the atmosphere for a few weeks. Assuming venting for 2 months at the full production rate expected for power generation and with a steam composition given in Table 9.1, the atmospheric discharges are calculated and listed in Figure 9.1. These are not yearly quantities, and are to be considered to occur once in the generating-plant lifetime, assuming that a producing well has a production life as long or longer than the life of the generating plant. Some audible sound would be expected to accompany the venting operations.

9.3 Turbine-Generator Operation

Of the 7.26×10^7 Te/yr of geothermal steam required for the 1000 MW(e) conceptual plant, 6.2% is required for auxiliary purposes, primarily to operate the ejectors which remove noncondensable gases from the condenser(1). The remainder of the steam expands through a low-pressure turbine and condenses at a pressure of 4 in Hg (abs). About 3.6% of the electrical power generated is used to operate coolant pumps, cooling tower blowers, and other plant equipment(1).

9.4 Air-Ejector Effluents

The noncondensable gases removed continuously by the steam ejector are released to the atmosphere. All the methane, nitrogen, argon, and hydrogen in the geothermal steam are released at this point, as are 86% of the CO_2, 87% of the NH_3, and 33% of the H_2S. These release fractions, and the calculated yearly releases, are given in Table 9.2.

Table 9.2

Yearly Quantities of Non-Condensable Gases

Emitted from Turbine Air Ejectors

Gas	Gas emitted by air ejector as percentage of gas in geothermal steam to power plant(7)	Yearly quantities emitted from 1000 Mw(e) power plant T/yr
CO_2	85%	497,000
NH_3	87%	43,900
CH_4	100%	36,300
H_2S	33%	12,100
N_2, A	100%	21,800
H_2	100%	7,290

9.5 Cooling System

The steam condensed in the contact condenser and the steam ejector condensate join the cooling water circulating between the condenser and the evaporative cooling tower. The circulating coolant increases 30°F in temperature as it passes through the condensers, requiring a total circulating flow for the 1000 Mw(e) conceptual plant of 910,000 gal/min. The total evaporation rate in the cooling tower is estimated to be 30,200 gal/min. A drift carryover of 0.05% of the circulating flow is assumed (cf. Section 4.2). The remainder of the steam condensate flows at a rate of 6840 gal/min into injection wells in the geothermal field, thereby serving as blowdown water to control the accumulation of non-volatiles in the circulating coolant.

About 10% of the CO_2 and 10% of the NH_3 in the geothermal steam follow the steam condensate and are volatilized in the cooling tower. About two thirds of the H_2S in the geothermal steam follows the condensate, and most of this is volatilized in the cooling tower. The remainder is reduced to sulfur and non-volatile sulfur compounds, which are returned with the blowdown condensate to the geothermal field. The quantity of H_2S volatilized in the cooling tower in the present flowsheet is calculated from a material balance on sulfur in the geothermal steam.

9.6 Disposal of Condensate Blowdown

The typical composition of the condensate returned to the geothermal field, and the calculated yearly quantities for the 1000 Mw(e) conceptual plant, are given in Table 9.3.

Table 8.3

Composition and Yearly Quantities in Condensate Return Water

Item	Concentration in condensate return[a] mg/liter	Yearly quantity for 1000 Mw(e) plant Te/yr
total alkalinity as HCO_3	429	5070
ammonia	148.3	1750
sulfide	2.0	23.6
sulfate	131.2	1548
free sulfur	8.35	98.5
nitrate	0.1	1.18
chloride	3.5	41.3
calcium	5.3	62.5
magnesium	1.0	11.8
silica	3.75	44.2
boron	17.1	202
total solids by evaporation	185.2	2190
organics and volatile solids	206.3	2440

On the basis of an estimated capacity of 1 million gallons per day for a single large injection well[6], the 1000 Mw(e) conceptual design would require about ten such wells for disposal of the condensate return.

9.7 Power Plant Land Area

The land requirement for the 1000 Mw(e) power plant, not including the land estimated previously for the geothermal wells, is about 100 acres, scaled from 2.5 acres for a 27 Mw(e) unit at Geysers[4].

REFERENCES

1. Finney, J. P., F. J. Miller, and D. B. Mills, "Geothermal Power Project of Pacific Gas and Electric Company at the Geysers, California," presented at the IEEE Power Engineering Society Summer Meeting (July 1, 1972).

2. McClure, H. K., Pacific Gas and Electric Company, Private Communication (October 12, 1972).

3. Ham, W. C., "Materials and Corrosion, Geysers Geothermal Power Plant," presented at National Association of Corrosion Engineers Conference, San Francisco, California (October 1, 1972).

4. Bruce, A. W. and D. B. Barton, Pacific Gas and Electric Company Mechanical Engineering Department, "Natural Steam Power Doubled by Unit 3 at the Geysers in California," (September, 1967).

5. Goldsmith, M., "Geothermal Resources in California; Potentials and Problems," California Institute of Technology, Environmental Quality Laboratory Report No. 5, p. 29 (December, 1971).

10. ELECTRICAL POWER FROM URANIUM-PLUTONIUM FUELED BREEDER REACTOR

10.1 Reactor Characteristics and Fuel Requirements

The fuel cycle flowsheet for a representative breeder reactor is shown in Figure 10.1. The flowsheet quantities are representative of a 1000 Mw(e) plant operating on a near-equilibrium fuel cycle, such that uranium and plutonium recovered from the discharge fuel are recycled and blended with natural or depleted make-up uranium and fabricated into fresh fuel. The equilibrium fuel cycle is attained only after several years of operation. During the first few years the entire uranium and plutonium in the fresh fuel must be obtained from outside sources, i.e., about 25 tonnes per year of natural or depleted uranium are required, and about 2.1 tonnes per year of plutonium must be obtained from the discharge fuel of water reactors or from the net plutonium product from other fast breeders which have reached their equilibrium fuel cycle.

The overall thermal efficiency of 41% is based upon data on the expected performance of a 1000 Mw(e) liquid-metal fast-breeder reactor(1) (LMFBR). The reactor core is composed of stainless-clad PO_2 - UO_2 fuel, containing 12.6 tonnes of plutonium and uranium. The core fuel operates at an average specific power of 174 Mw(t) per tonne of uranium-plutonium mixture. Core fuel is discharged after an average thermal exposure of 80,000 Mw days per tonne, corresponding to core-fuel operating life of 460 full-power days. About 10 tonnes of core fuel are discharged yearly for reprocessing (at 100% load factor).

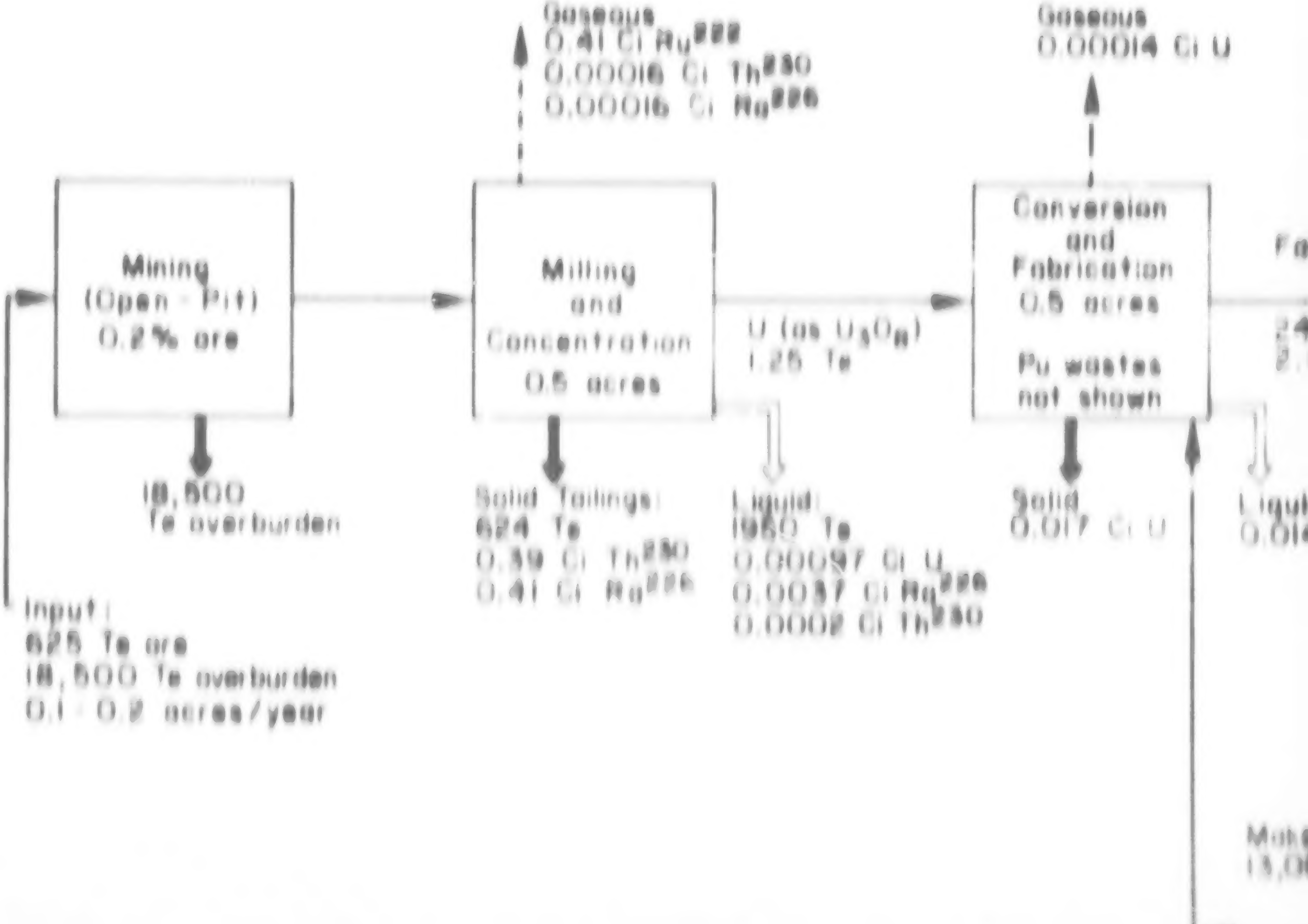
FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

〰〰➤ ELECTRICAL ENERGY
- - - - ➤ AIRBORNE RELEASE
⇨ LIQUID EFFLUENT
➡ SOLID EFFLUENT

Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keeton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

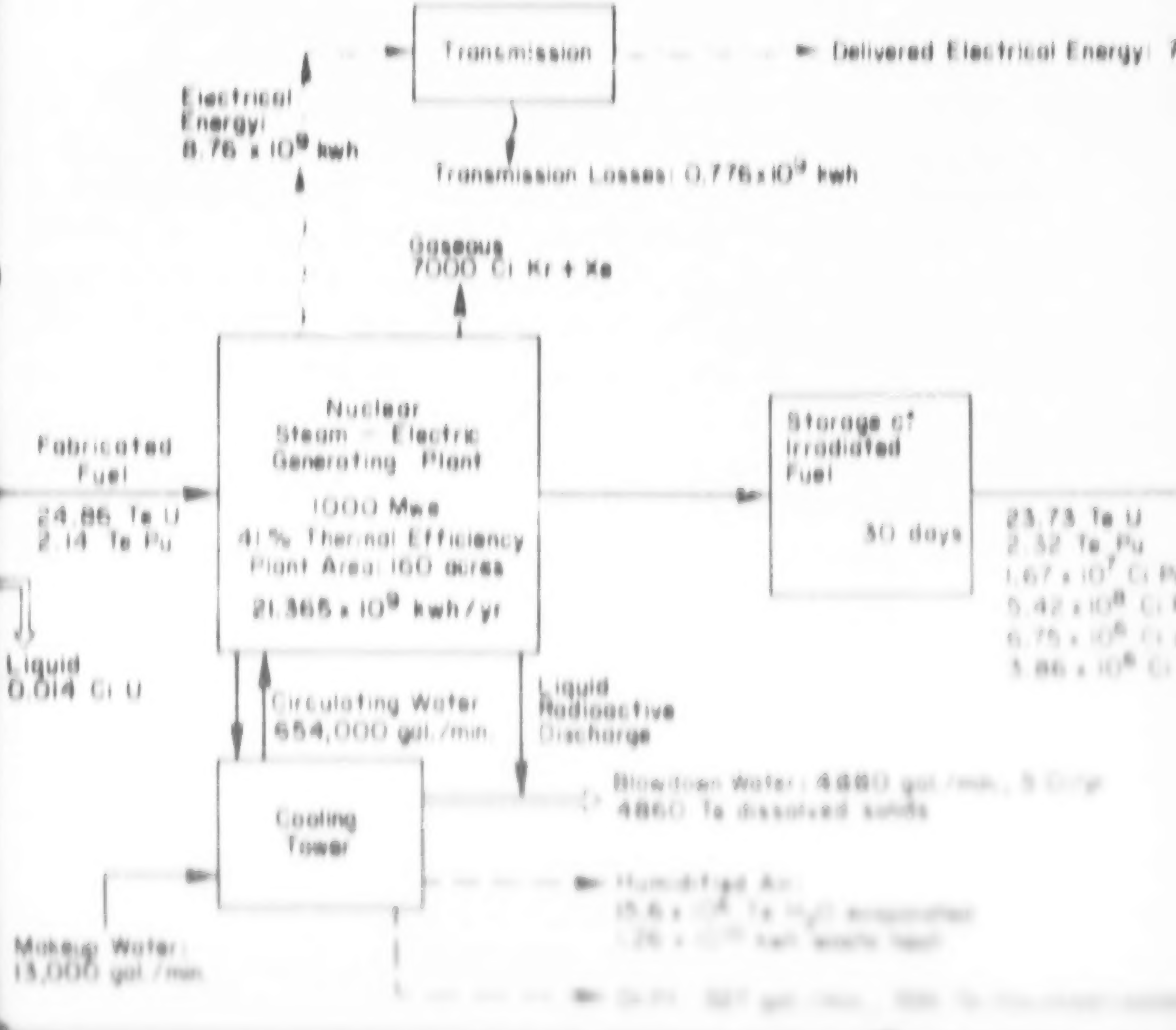
TEKNEKRON INC.
BERKELEY, CALIFORNIA



Gaseous
0.41 Ci Rn^{222}
0.00016 Ci Th^{230}
0.00016 Ci Ra^{226}
Gaseous
0.00014 Ci U
Mining
(Open - Pit)
0.2% ore
Milling
and
Concentration
0.5 acres
U (as U_3O_8)
1.25 Te
Conversion
and
Fabrication
0.5 acres
Pu wastes
not shown
Fa
24
2.
18,500
Te overburden
Solid Tailings:
624 Te
0.39 Ci Th^{230}
0.41 Ci Ra^{226}
Liquid:
1950 Te
0.00097 Ci U
0.0037 Ci Ra^{226}
0.0002 Ci Th^{230}
Solid
0.017 Ci U
Liqui
0.01
Input:
625 Te ore
18,500 Te overburden
0.1 - 0.2 acres/year
Mob
13,0

Figure 10.1

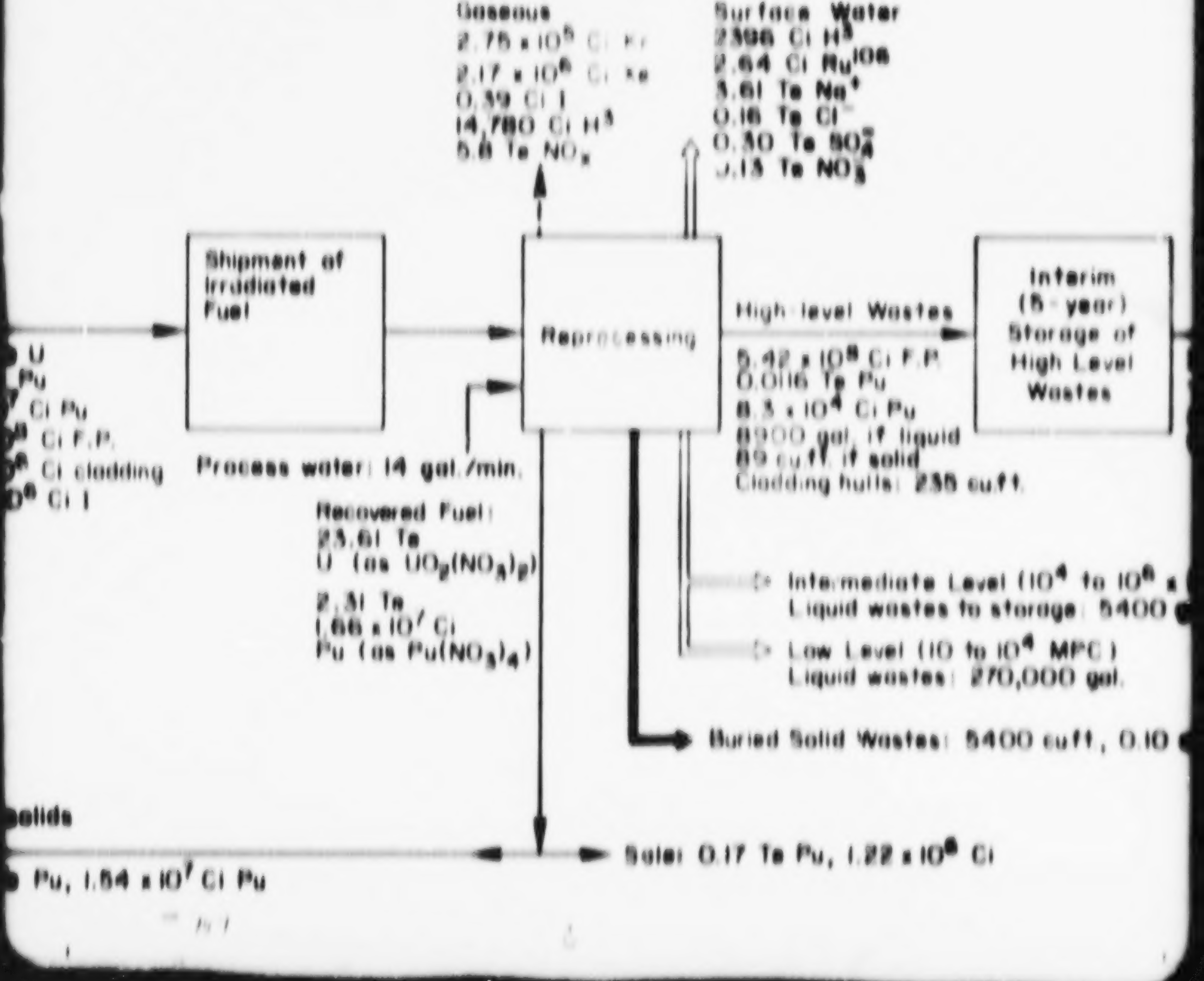
Breeder Reactor Nuclear Pow
Material And Environmental

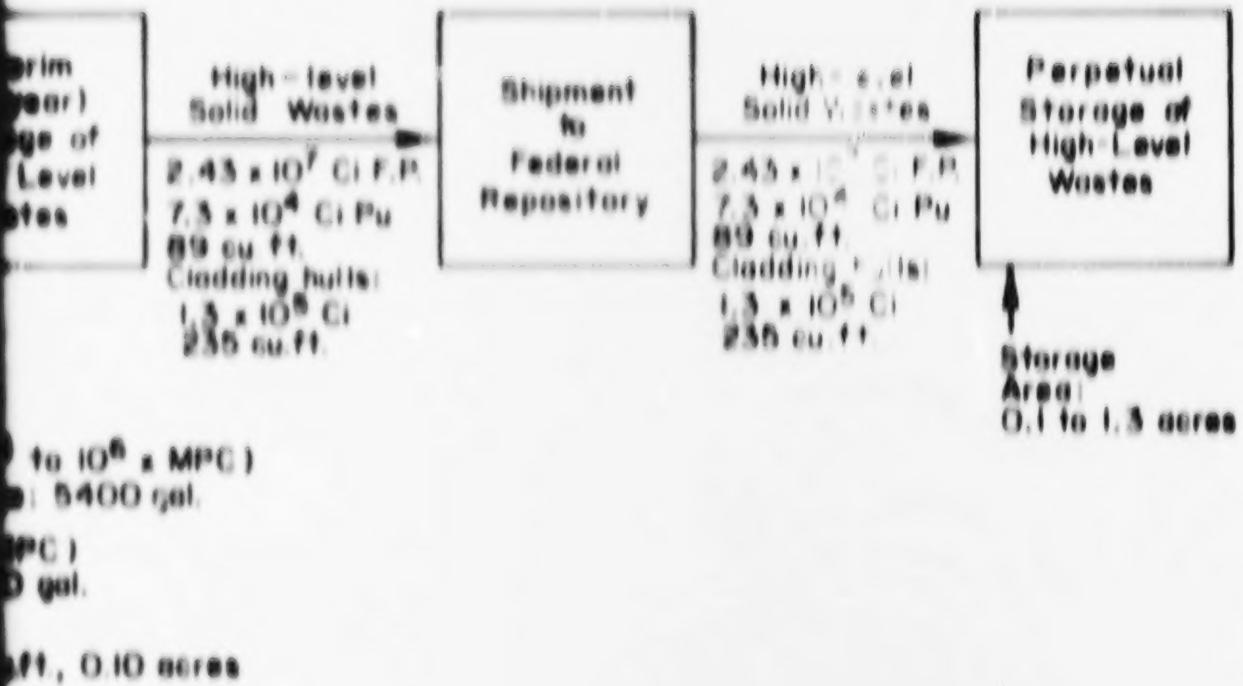

Transmission
Delivered Electrical Energy: 7
Electrical Energy: 8.76 x 10^9 kwh
Transmission Losses: 0.776 x 10^9 kwh
Gaseous 7000 Ci Kr + Xe
Nuclear Steam - Electric Generating Plant
1000 Mwe
41% Thermal Efficiency
Plant Area: 160 acres
21.365 x 10^9 kwh/yr
Fabricated Fuel
24.86 Te U
2.14 Te Pu
Liquid 0.014 Ci U
Storage of Irradiated Fuel
30 days
23.73 Te U
2.32 Te Pu
1.67 x 10^7 Ci P
5.42 x 10^8 Ci
6.75 x 10^8 Ci
3.86 x 10^8 Ci
Circulating Water 654,000 gal./min.
Liquid Radioactive Discharge
Blowdown Water: 4880 gal./min., 5 Ci/yr
4860 Te dissolved solids
Cooling Tower
Humidified Air:
15.6 x 10^6 Te H2O evaporated
1.26 x 10^10 kwh waste heat
Makeup Water: 13,000 gal./min.

.1

ower Plant 1000 Mwe
tal Release Flowsheet

rgy: 7.984 x 10⁹ kwh


Gaseous
2.75 x 10⁵ Ci Kr
2.17 x 10⁶ Ci Xe
0.39 Ci I
14,780 Ci H³
5.8 Te NOx
Surface Water
2396 Ci H³
2.64 Ci Ru¹⁰⁶
3.61 Te Na⁺
0.16 Te Cl⁻
0.30 Te SO₄⁼
0.15 Te NO₃⁻
Shipment of Irradiated Fuel
Reprocessing
High-level Wastes
Interim (5-year) Storage of High Level Wastes
U
Pu
⁷ Ci Pu
⁸ Ci F.P.
⁶ Ci cladding
⁶ Ci I
5.42 x 10⁸ Ci F.P.
0.0116 Te Pu
8.5 x 10⁴ Ci Pu
8900 gal. if liquid
89 cu.ft. if solid
Cladding hulls: 235 cu.ft.
Process water: 14 gal./min.
Recovered Fuel:
23.61 Te
U (as UO₂(NO₃)₂)
2.31 Te
1.66 x 10⁷ Ci
Pu (as Pu(NO₃)₄)
Intermediate Level (10⁴ to 10⁶ x
Liquid wastes to storage: 5400
Low Level (10 to 10⁴ MPC)
Liquid wastes: 270,000 gal.
Buried Solid Wastes: 5400 cu.ft., 0.10
olids
Sale: 0.17 Te Pu, 1.22 x 10⁶ Ci
Pu, 1.54 x 10⁷ Ci Pu


rim
year)
ge of
Level
stes
High-level Solid Wastes
2.43 x 10^7 Ci F.P.
7.3 x 10^4 Ci Pu
89 cu ft.
Cladding hulls:
1.3 x 10^5 Ci
235 cu.ft.
Shipment to Federal Repository
High-level Solid Wastes
2.43 x 10^7 Ci F.P.
7.3 x 10^4 Ci Pu
89 cu ft.
Cladding hulls:
1.3 x 10^5 Ci
235 cu.ft.
Perpetual Storage of High-Level Wastes
Storage Area:
0.1 to 1.3 acres
to 10^6 x MPC)
: 5400 gal.
PC)
gal.
ft, 0.10 acres

TEKNEKRON, INC.

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

D

Surrounding the core is a blanket containing about 20 tonnes of uranium, a small fraction of which will have been converted to plutonium by absorbing neutrons which diffuse into the blanket from the core.

The total radioactivity in the yearly amount of fuel discharge, at the time of discharge, is greater for the fast breeder reactor than for the light-water plant because of the more frequent replacement of core fuel in the breeder*.

Heat and fission products are generated in the blanket by fast-fission in U^{238} and by fission of plutonium that has been formed. Periodically, blanket elements are discharged to recover the plutonium, to be recycled as core fuel.

The total discharge rate of core and blanket fuel is 27 tonnes per year, containing 2.32 Te/yr of plutonium, with plutonium radioactivity of 28 million curies, at the time of discharge.

10.2 Cooling Irradiated Fuel

It is planned(3) that fast-breeder fuel will be stored for 30 days at the reactor before it is shipped for reprocessing. This is shorter than the 150-day storage period planned for light-water nuclear plants because of the economic incentive to minimize plutonium inventories in the fast-breeder fuel cycle. The yearly amounts of plutonium in the fast-breeder fuel cycle are about eight-fold greater than in the light-water nuclear plant, when the latter is fueled with slightly enriched uranium without plutonium recycle. The greater the fuel cycle inventory, the longer the fast-breeder must operate on purchased plutonium make-up fuel before it can reach its equilibrium fuel cycle. Therefore, there is considerable incentive to reduce holdup time in all the fast-breeder fuel-cycle operations. This introduces new problems in fuel reprocessing because of the large amount, 3.86 million curies/yr, of radioactive iodine fission products remaining after 30 days.

---

*These flowsheets are based on an estimated average core fuel life of 400 full-power days for the breeder and 3 years for the light-water reactor.

Shorter cooling also results in about a four-fold greater amount of radioactivity in the shipped fast breeder fuel. This increases the shielding requirement for shipping containers and the rate of heat-generation in the fuel due to radioactive decay. Even for the same cooling time, the heat generation rate in shipped fast-breeder core fuel, per unit mass of fuel, is about six times greater than in light-water fuel, because of the higher average specific power at which the breeder core fuel operates. Shipping short-cooled breeder core fuel will impose more stringent requirements for shipping-container design than for water-reactor fuel.

10.3 Radiological Releases from Reactor

The radiological releases for the liquid-metal fast breeder are difficult to predict at this time. According to the environmental statement(3) for the proposed 380 Mw(e) LMFBR demonstration plant, noble-gas radionuclides released into the sodium cover gas system* will be separated by a process such as cryogenic distillation, bottling, and storage. However, for the present flowsheet a noble gas release of 7000 Ci/yr is assumed, which will meet the expectation(3) of a release resulting in a site-boundary dose of less than one percent of natural background.

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*The cover gas may also contain 1.83-hr A^{41} resulting from neutron activation of argon.

It is likely that radioiodine releases might be quite small because iodine fission products escaping from fuel rods will react with sodium coolant to form NaI.

The total rate of tritium production is somewhat greater in a fast-breeder reactor than in a light-water reactor*, and more tritium is expected to escape from fuel into the coolant because of the use of stainless steel fuel cladding and the higher cladding temperatures. However, once in the coolant, the tritium reacts with sodium to form sodium tritide, most of which will be removed in the cold-trap filter system for purification. No environmental releases of tritium at the reactor plant are projected in the LMFBR Demonstration Plant environmental statement(3). However, a liquid release of 16 Ci/yr of tritium is estimated for the 400 Mw(t) FFTF** reactor now under construction. This scales to about 100 Ci/yr of tritium from the 1000 Mw(e) fast breeder in the present flowsheet. No non-tritium radioactive liquid effluents are indicated in the Demonstration Plant environmental statement(3). The described process of evaporation and ion exchange is effective in concentrating wastes for solidification and storage as solids. For the purpose of the present flowsheet, 5 Ci/yr is assumed, typical of radioactive effluents from light-water plants with similar liquid-waste management systems.

---

*It is estimated that 25,000 Ci/yr of tritium is produced from fission in the 1000 Mw(e) fast breeder.

**Fast Flux Test Facility, a sodium-cooled fast-spectrum reactor designed to test fast-breeder fuel.

Neutron absorption in the sodium coolant results in about 70 million curies of 14.96-hr Na^{24} and 600 curies of 2.62-yr Na^{22}. Sodium leaks and spills are of some concern, and if the spilled sodium contacts air it can oxidize to an aerosol containing activated sodium, fission products, and other radionuclides which may be present in the sodium. Extensive precautions are taken to prevent spills and to minimize the chances of anything but chemically inert gas coming into contact with sodium. No releases of radioactive sodium are projected for the LMFBR Demonstration Plant(3) or for normal operation of the FFTF(4), and no sodium releases are indicated on the present flowsheet.

The 1000 Mw(e) fast breeder reactor will contain about 1.8 to 2.8 tonnes of plutonium(3) corresponding to 2.2 to 3.5 million curies* of plutonium. No environmental releases of plutonium are projected for the LMFBR Demonstration Plant(3) or for normal operation of the FFTF(4), and none are indicated in Figure 10.1.

10.4 Mining, Milling and Fuel Fabrication

Environmental quantities associated with mining and milling natural uranium make-up fuel for the equilibrium breeder fuel cycle are based upon data presented in Section 2.2 and 2.3, scaled according to uranium throughput. Mining and milling would be eliminated if the make-up uranium were obtained from the presently stored depleted UF_6 tails from isotope separation plants. Alternatively, the make-up uranium could be obtained from the depleted tails produced in a system generating electrical power from reactors operating on enriched uranium make-up fuel as well as from breeder reactors.

---

*Including radioactivity of 4.98-hr Pu^{241}.

Environmental effluents associated with UF_6 conversion and isotope separation and the associated electrical energy consumption are not present in the equilibrium breeder flowsheet.

Fabrication effluents are based upon data on UO_2 fabrication in Section 2.6 scaled according to uranium throughput. Limestone neutralization of fluorides is not present here because of the elimination of processes requiring UF_6. No plutonium effluents are indicated for the fabrication operation because of lack of data on plutonium losses. As explained in Section 2.12, the fractional losses of plutonium must be kept extremely small, and this problem is even more acute in fabricating breeder fuel because of the larger quantities of plutonium involved.

10.5 Shipment of Irradiated Fuel

The short 30-day cooling period (cf. Section 10.2) for irradiated fuel introduces special considerations in the design of shipping containers. Otherwise, the environmental considerations of shipping appear to be similar to those discussed in Section 2.8.

10.6 Fuel Reprocessing

The technology contemplated for reprocessing breeder core and blanket fuel is basically the same as that involved in processing water reactor fuel. One new consideration does result from the considerably higher fissile content of fuel discharged from the breeder core, requiring more stringent precautions to avoid criticality during dissolution and during the early stages of chemical separation. Another consideration arises from the relatively large amount (3.88 million curies/yr) of radioiodine fission products remaining after 30 days of cooling*. An overall iodine decontamination factor of only 1000, as was assumed for light-water reactor fuel reprocessing, would be completely inadequate here. Additional iodine recovery technology, such as that discussed in Section 2.9, must be installed**, and it is planned to incorporate such technology when LMFBR demonstration fuel is reprocessed$^{(3)}$. It is projected$^{(2)}$ that with this additional technology an overall iodine decontamination factor of about 10^7 can be achieved, resulting in an estimated iodine release of 0.388 Ci/yr.

In Section 2.9 several new chemical processes which could be applied, if needed, to reduce effluents of noble gas radionuclides and tritium at fuel reprocessing plants are discussed. The environmental statement$^{(3)}$ for the LMFBR Demonstration Plant indicates that these new chemical processes will be applied to reprocessing demonstration-plant breeder fuel as well as to the later reprocessing of fuel from 1000 Mw(e) breeders, resulting in the reduction in concentration by a factor of 100 for noble-gas radionuclides and 10 for tritium.

---

*Water-reactor fuel cooled 150 days contains 61 curies/yr of radioiodine, as shown in Table 2.1.

**One alternate to incorporating additional iodine recovery technology is to cool the discharge fuel for a longer period.

However, it is not apparent why, in reprocessing breeder fuel, there should be any incentive to reduce noble-gas radionuclide releases and tritium releases below the levels now acceptable for light-water reactor fuels. There is, in fact, somewhat less Kr^{85} produced in the breeder fuel (275,000 Ci/yr) than in the water-reactor fuel (373,000 Ci/yr) and the tritium production is only slightly greater in the breeder. If there is incentive to reduce releases of Kr^{85} and H^3 at fuel reprocessing plants, it would apply equally well to water reactors and breeder reactors, and the technology would be essentially the same*. Therefore, the present flowsheets show all Kr^{85} and H^3 released to the environment at the fuel reprocessing plant for both the breeder reactor and the light-water reactor.

The remaining environmental effluents for breeder fuel reprocessing are calculated according to data in Section 7.9 scaled according to fuel throughput.

10.7 Management of High Level Radioactive Wastes

The technology and environmental quantities associated with the management of high-level wastes from fast-breeder fuel reprocessing are very much the same as those described in Section 2.16. The fission-product quantities are calculated specifically for the fast breeder plant$^{(1,2)}$. The volumes of wastes are scaled on the basis of total fission product mass$^{(2)}$.

---

*Recognizing some differences in H^3 recovery by voloxidation because of differences in fuel cladding and fuel composition.

Assuming that 0.5% of the plutonium processed remains with the high-level wastes$^{(2)}$, the breeder high-level wastes will contain about eight times more plutonium than the high-level wastes from the light-water plant.

As in the case of water reactors, plutonium is one of the main contributors to radioactivity in high-level waste after a few hundred years of storage (cf. Figure 2.4). For shorter storage periods, e.g., 100 years, Cs^{137} and Sr^{90} are the most significant contributors to total radioactivity. As compared with the light water nuclear plant, the fast breeder is calculated to produce 20 percent less Cs^{137} and over 50% less Sr^{90}.

10.8 Accidental Environmental Releases

Estimates of accidental environmental releases are not included because of lack of meaningful data and analyses (cf. Section 2.11).

REFERENCES

1. Arnold, E. D., *Phoebe-A Code for Calculating Beta and Gamma Activity and Spectra for ^{235}U Fission Products*, ORNL-3931, USAEC (July, 1966).

2. *Siting of Fuel Reprocessing and Waste Management Facilities*, ORNL-4451 (USAEC) (July, 1970).

3. U.S. Atomic Energy Commission, *Environmental Statement for Liquid Metal Fast Breeder Reactor Demonstration Plant*, WASH-1509 (April, 1972).

4. U.S. Atomic Energy Commission, *Environmental Statement, Fast Flux Test Facility*, Richland, Washington, WASH-1510 (May, 1972).

11. ELECTRICAL POWER FROM SOLAR ENERGY

11.1 Introduction

The fuel cycle flowsheet shown in Figure 11.1 illustrates one of the proposed means of converting solar energy to electrical energy. Based upon a concept proposed by Meinel[(1)], solar energy incident upon flat plate energy collectors heats liquid sodium-potassium alloy (NaK) to about 200°C. The circulating hot liquid metal transports the collected solar heat to a boiler where low-pressure steam is generated. The steam expands through a low-pressure turbine and is condensed by water coolant circulating from the condenser to an evaporative cooling tower. The quantity of sodium-potassium alloy provides sufficient energy storage for continuous power generation.

The net electrical output from the power plant is 4.7% of the solar energy incident upon the collectors, requiring an annual incident solar energy of 1.885×10^{11} kwh(t) for a 1000 Mw(e) conceptual power plant operating at 100% load factor.

11.2 Solar Energy Collection

The solar energy collectors are designed to maximize the transmission of incident solar energy to the NaK coolant and to minimize the radiative energy loss from the heated coolant. The high absorptivity collector plates are housed in evacuated containers of glass or other transparent material. The plates are assumed to have an absorptivity of

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

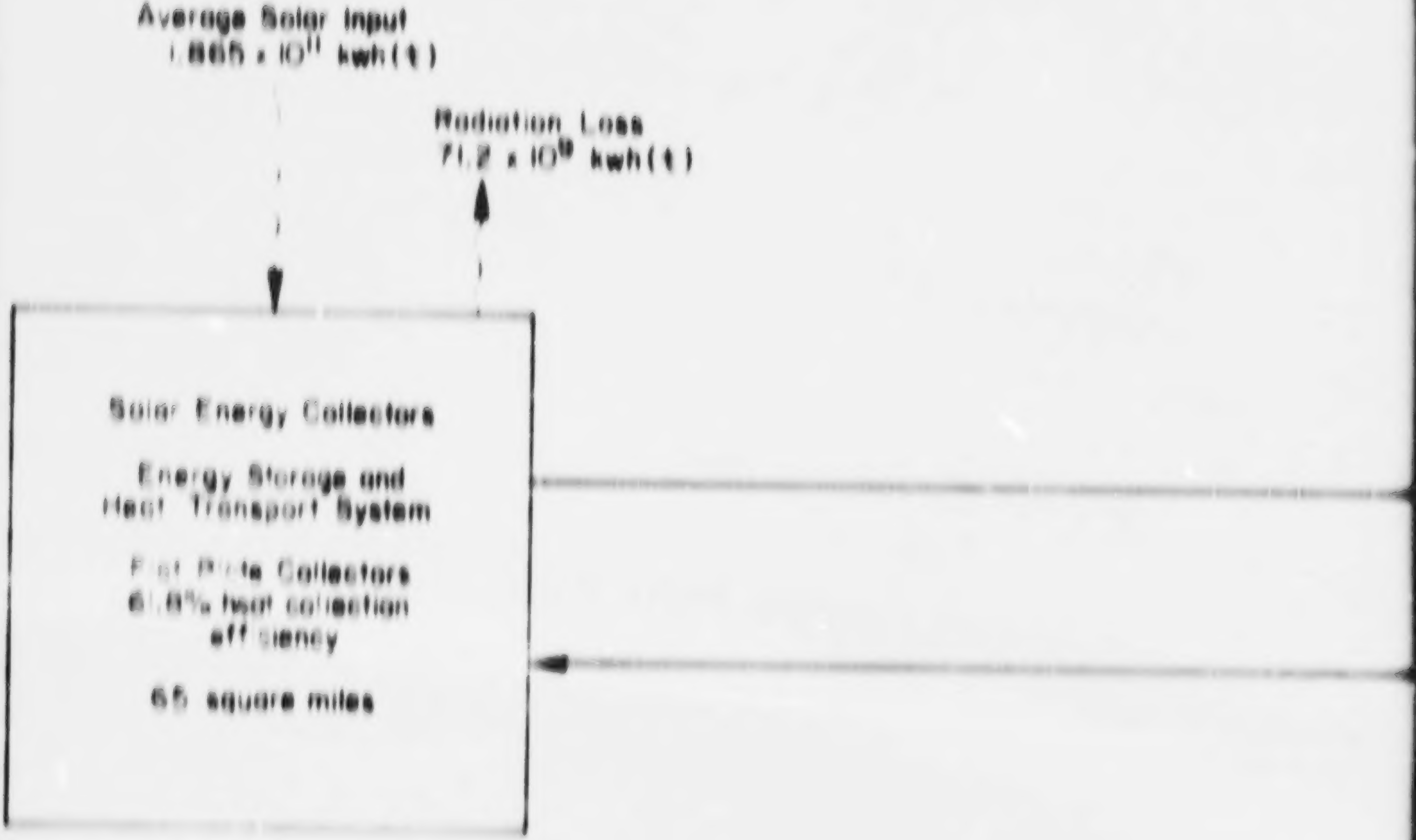
〰〰〰► ELECTRICAL ENERGY
- - - - - ► AIRBORNE RELEASE
═════▷ LIQUID EFFLUENT
━━━━➡ SOLID EFFLUENT

Te = METRIC TONNES
Ci = CURIES
kwh = KILOWATT-HOURS
Mw(e) = MEGAWATTS ELECTRICAL
MPC = MAXIMUM PERMISSABLE CONCENTRATION

Principal Investigator: Dr. T.H. Pigford
Project Director: Dr. M.J. Keaton
EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

TEKNEKRON, INC.
BERKELEY, CALIFORNIA

Solar Power P
Material And



Average Solar Input
1.865 x 10^{11} kwh(t)

Radiation Loss
71.2 x 10^{9} kwh(t)

Solar Energy Collectors

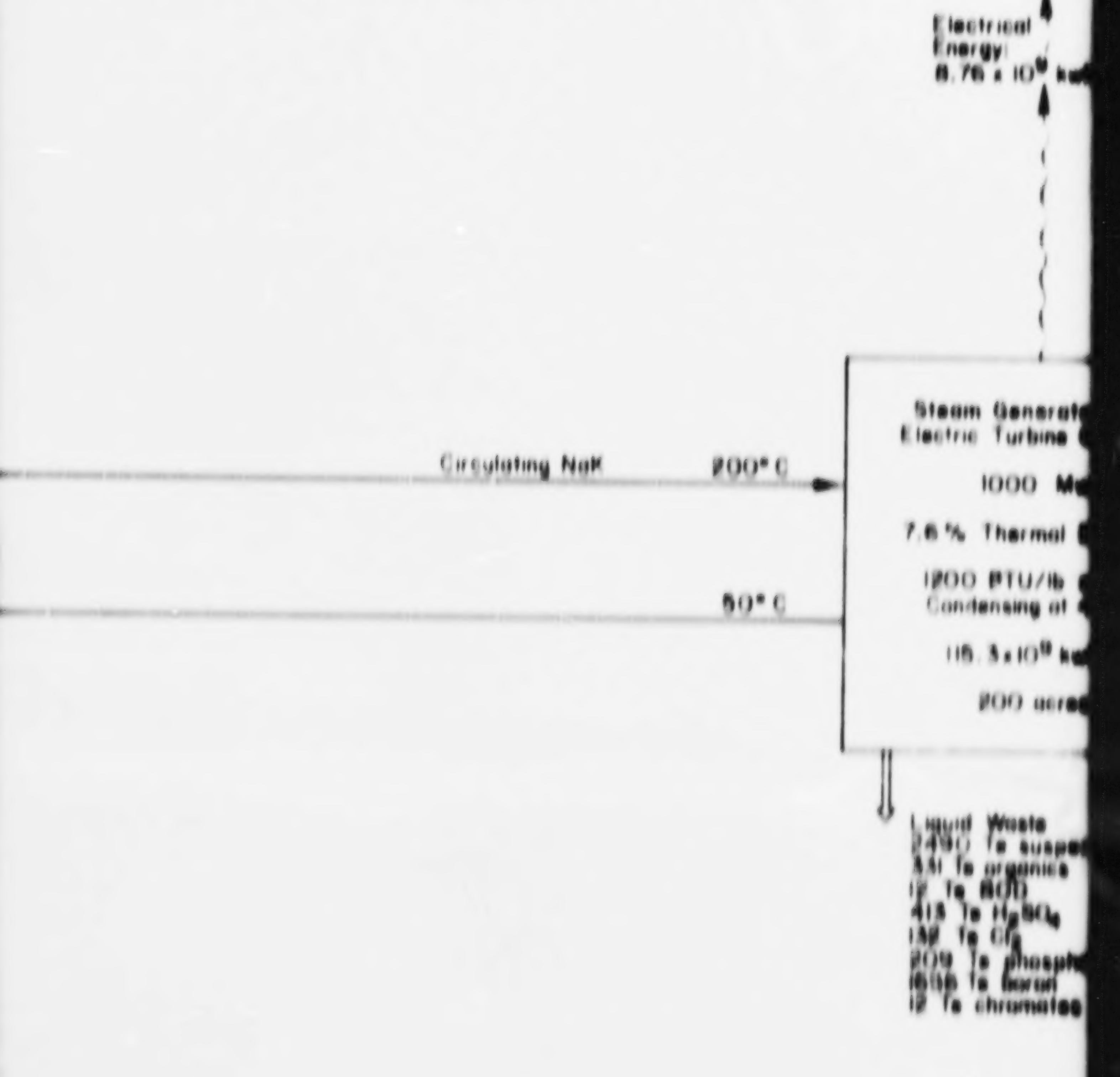
Energy Storage and
Heat Transport System

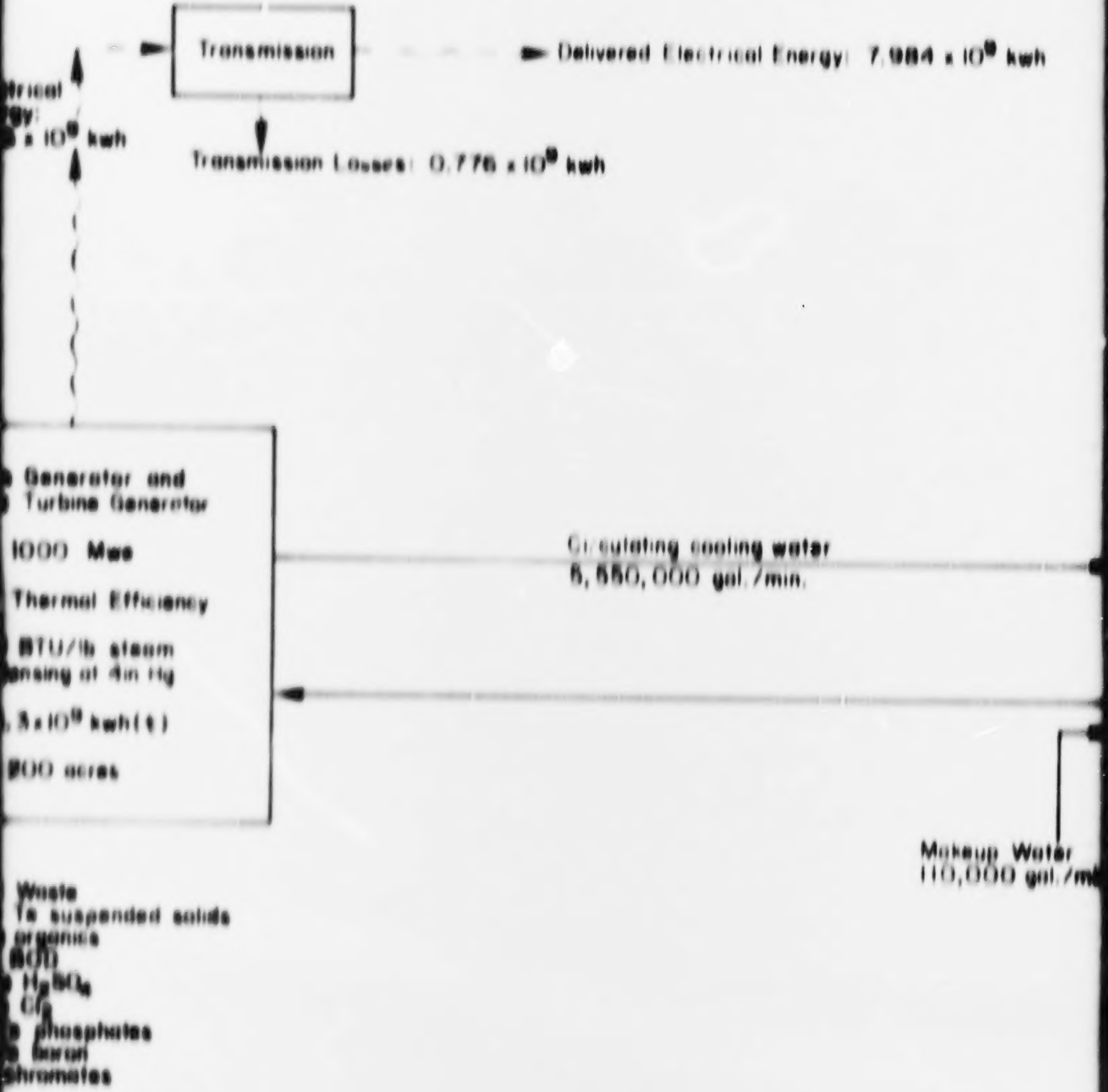
Flat Plate Collectors
61.8% heat collection
efficiency

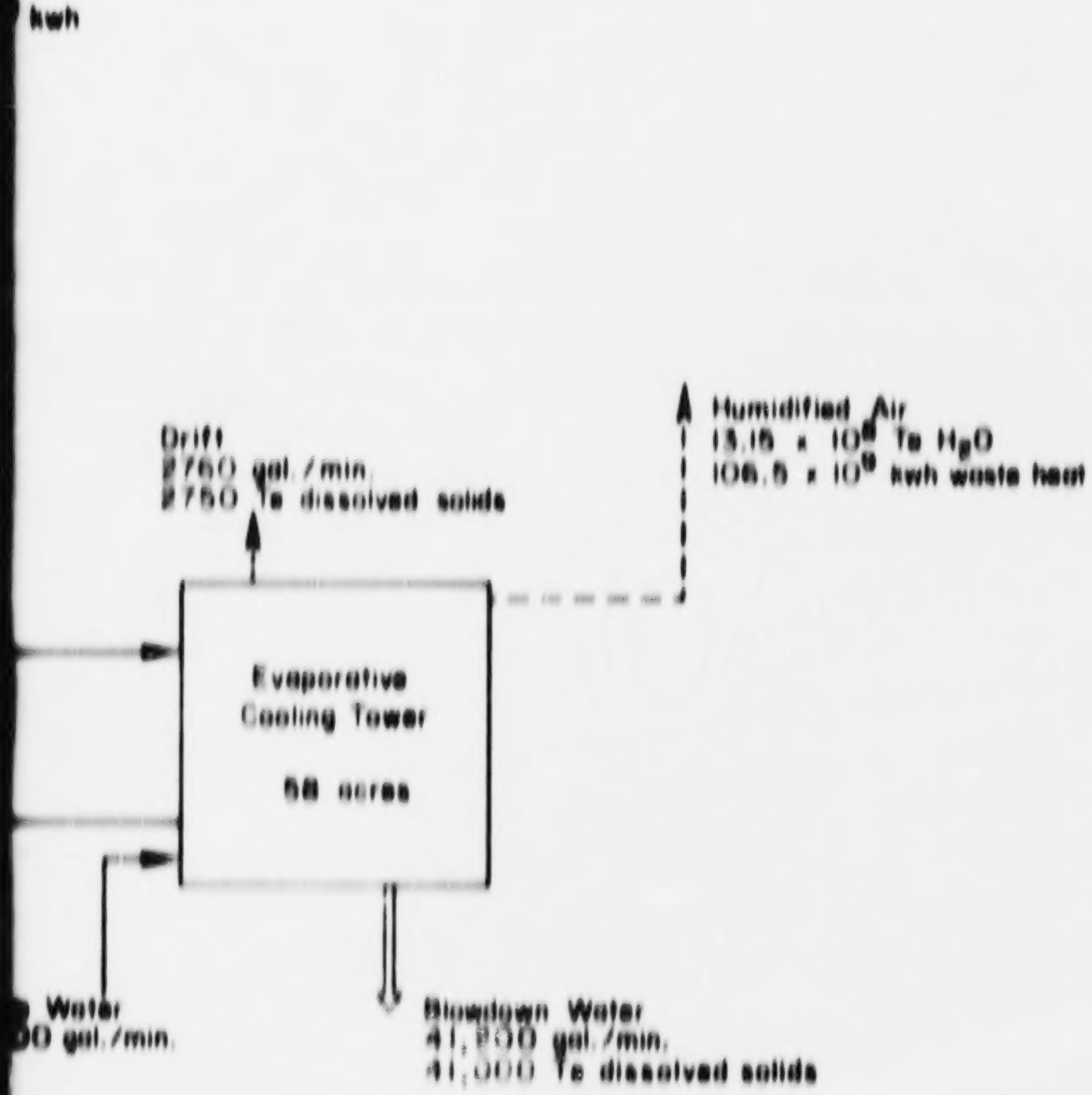
65 square miles

Figure 11.1

...ver Plant 1000 Mwe
And Environmental Release Flowsheet


Electrical
Energy:
8.76 x 10^9 kw
Steam Generat
Electric Turbine
1000 M
7.6 % Thermal
1200 BTU/lb
Condensing at
115.3x10^9 kw
200 acres
Circulating NaK
200° C
50° C
Liquid Waste
2490 Te suspe
331 Te organics
12 Te BOD
415 Te H_2SO_4
132 Te Cl_2
209 Te phospha
1606 Te boron
12 Te chromates


Transmission
Delivered Electrical Energy: 7.984 x 10⁹ kwh
trical
rgy:
3 x 10⁹ kwh
Transmission Losses: 0.776 x 10⁹ kwh
Generator and
Turbine Generator
1000 Mwe
Thermal Efficiency
BTU/lb steam
ensing at 4in Hg
,3 x 10⁹ kwh(t)
200 acres
Circulating cooling water
5,550,000 gal./min.
Makeup Water
110,000 gal./m
Waste
To suspended solids
organics
BOD
H_2SO_4
Cl_2
phosphates
boron
chromates


kwh
Drift
2760 gal./min.
2750 Te dissolved solids
Humidified Air
13.15 x 10^6 Te H_2O
106.5 x 10^9 kwh waste heat
Evaporative
Cooling Tower
58 acres
Water
00 gal./min.
Blowdown Water
41,200 gal./min.
41,000 Te dissolved solids

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Project Director: Dr. M.J. Keaton
Research Associate: B.J. Mann

0.93 for the incident solar spectrum, a low-temperature emissivity of 0.10, and a back-side emissivity of 0.05(8). Analyses by Hottel and Howard(8), taking into account radiant energy absorption and re-emission and the time-dependence of the angle of solar incidence, predict an overall heat collection efficiency of 61.0%. The incident energy not collected is re-radiated.

For the average dail solar energy input at a location such as El Paso, Texas, the average rate of collection of thermal energy is estimated to be 0.155 thermal kilowatts per square meter of collector surface. For the 1000 MW(e) conceptual power plant this corresponds to a collector area of 32.7 square miles. Assuming the actual land area required for the collectors and primary heat transfer system is twice the collector area(8), a total land area of about 65 square miles is required for energy collection and transport.

11.3 Turbine Generator Operation

Assuming, optimistically, that saturated steam is generated at the NaK temperature of 200°C and expands through a turbine to a condenser pressure of 4 in. Hg (abs), about 7.6% of the collected thermal energy is converted to electrical energy. It is assumed that all of the generated electrical energy appears as the electrical product.

The only significant chemical wastes created are those associated with boiler blowdown. An estimate is obtained by scaling the yearly quantities report (cf. Section 8.8) for the fossil fuel power plants on the basis of the power-plant thermal input. The results are shown in

Table 11.1.

Table 11.1
Boiler Blowdown Releases

	Annual quantity released by 1000 Mw(e) solar power plant Te/yr
suspended solids	2400
organics	331
BOD	12
H_2SO_4	413
Cl_2	132
phosphates	200
boron	1486
chromates	12

Unknown environmental releases may be associated with the NaK system, but no estimates are currently available.

A land area of 100 to 200 acres is assumed to be required for the generating equipment(3).

11.4 Cooling System

A total of 100.5 x 10^9 per year of thermal energy is rejected from the condenser to an evaporative cooling system. Scaled from the data in Section 6.2, about 5,500,000 gal/min of circulating water and 110,000 gal/min of make-up water are required, with about 60 acres alloted for the cooling system.

11.6 Electrical Energy Transmission

There would be a considerable premium on locating solar energy power plants in areas where high average solar input could be relied upon. This might then require more extensive transmission systems than for other types of power plants.

REFERENCES

1. Meinel, A. B. and M. P. Meinel, "Is It Time for a New Look at Solar Energy?" *Bulletin of the Atomic Scientists* 27:8, pp. 32-37 (October, 1971).

2. Hottel, H. C. and J. B. Howard, "New Energy Technology, Some Facts and Assessments," MIT Press (1971).

3. "Considerations Affecting Steam Power Plant Site Selection," Energy Policy Staff, Office of Science and Technology, Washington, D.C. (December, 1968).

12. ELECTRICAL POWER FROM THERMONUCLEAR FUSION

12.1 Energy Producing Reactions

The flowsheet shown in Figure 12.1 is based upon the conceptual design of a fusion power plant described by Steiner and Fraas(1), extrapolated to an electrical power production of 1000 Mw(e). The fusion reactions assumed are(2):

$H^2 + H^3 = He^4 + n^1$ 1.02 x 10^{11} n/sec per watt thermal

$H^2 + H^2 = He^3 + n^1$ 2.96 x 10^{10} n/sec per watt thermal

The reacting core is surrounded by a lithium blanket, where make-up tritium for the core is produced according to the reactions

$Li^6 + n^1 = H^3 + He^4$

$Li^7 + n^1 = H^3 + He^4 + n^1$

The tritium production rate quoted by Steiner(2) is equivalent to a production rate of 2.16 x 10^{11} atoms of tritium per watt thermal.

12.2 Power Conversion

The Steiner-Fraas(1) design contemplates heat extraction from the blanket by boiling potassium. The potassium vapor expands through a

FLOW QUANTITIES ARE STATED IN METRIC TONNES/YEAR
UNLESS OTHERWISE INDICATED
100% LOAD FACTOR
EVAPORATIVE COOLING TOWER FOR WASTE HEAT REJECTION

∿∿∿→ ELECTRICAL ENERGY
- - - → AIRBORNE RELEASE
⇨ LIQUID EFFLUENT
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Te : METRIC TONNES
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Mw(e) : MEGAWATTS ELECTRICAL
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Principal Investigator: Dr. T.H. Pigford
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EPA Project Officer: Paul H. Gerhardt
EPA No. 68-01-0561
Standards Research Branch

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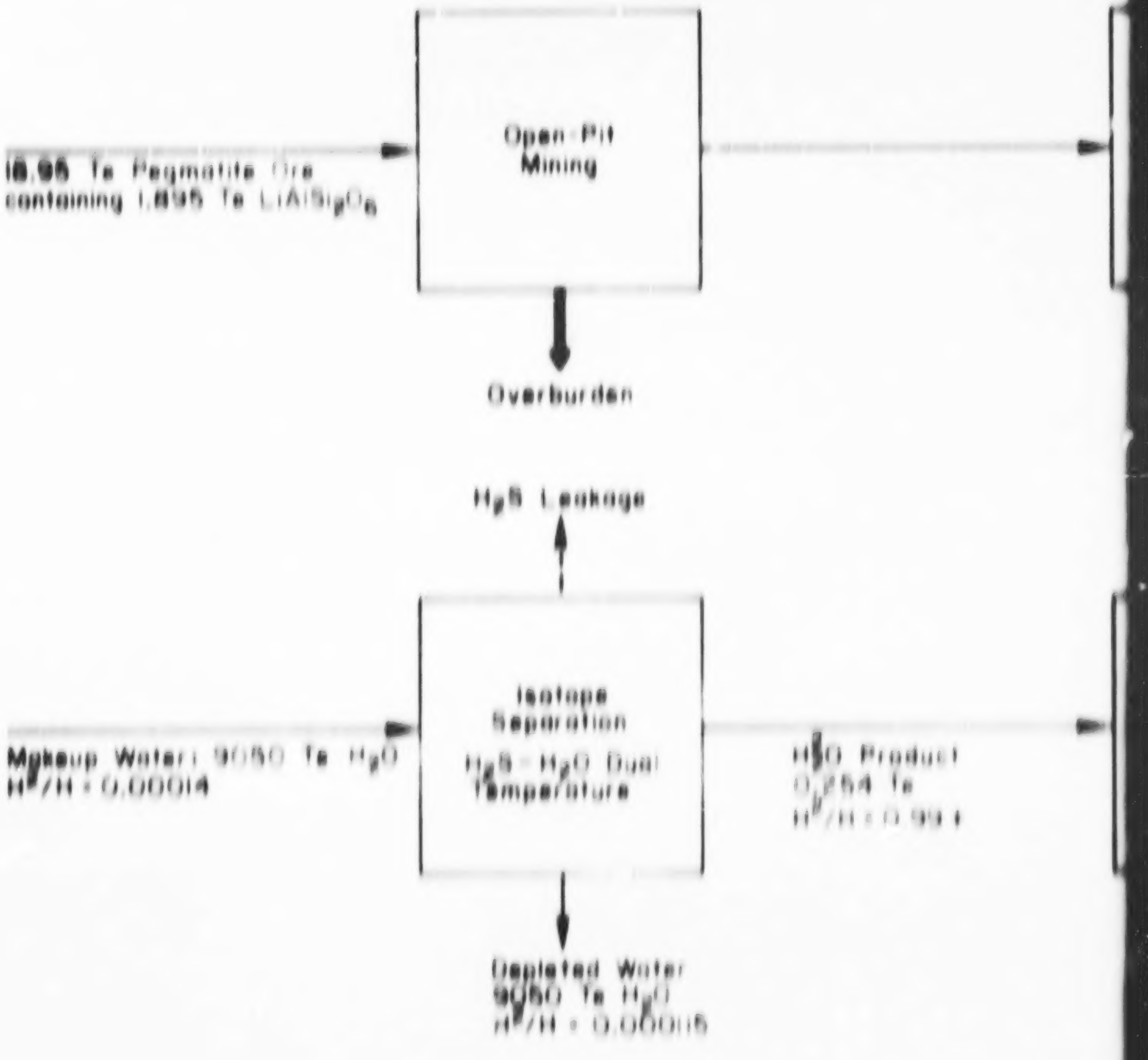
BERKELEY, CALIFORNIA

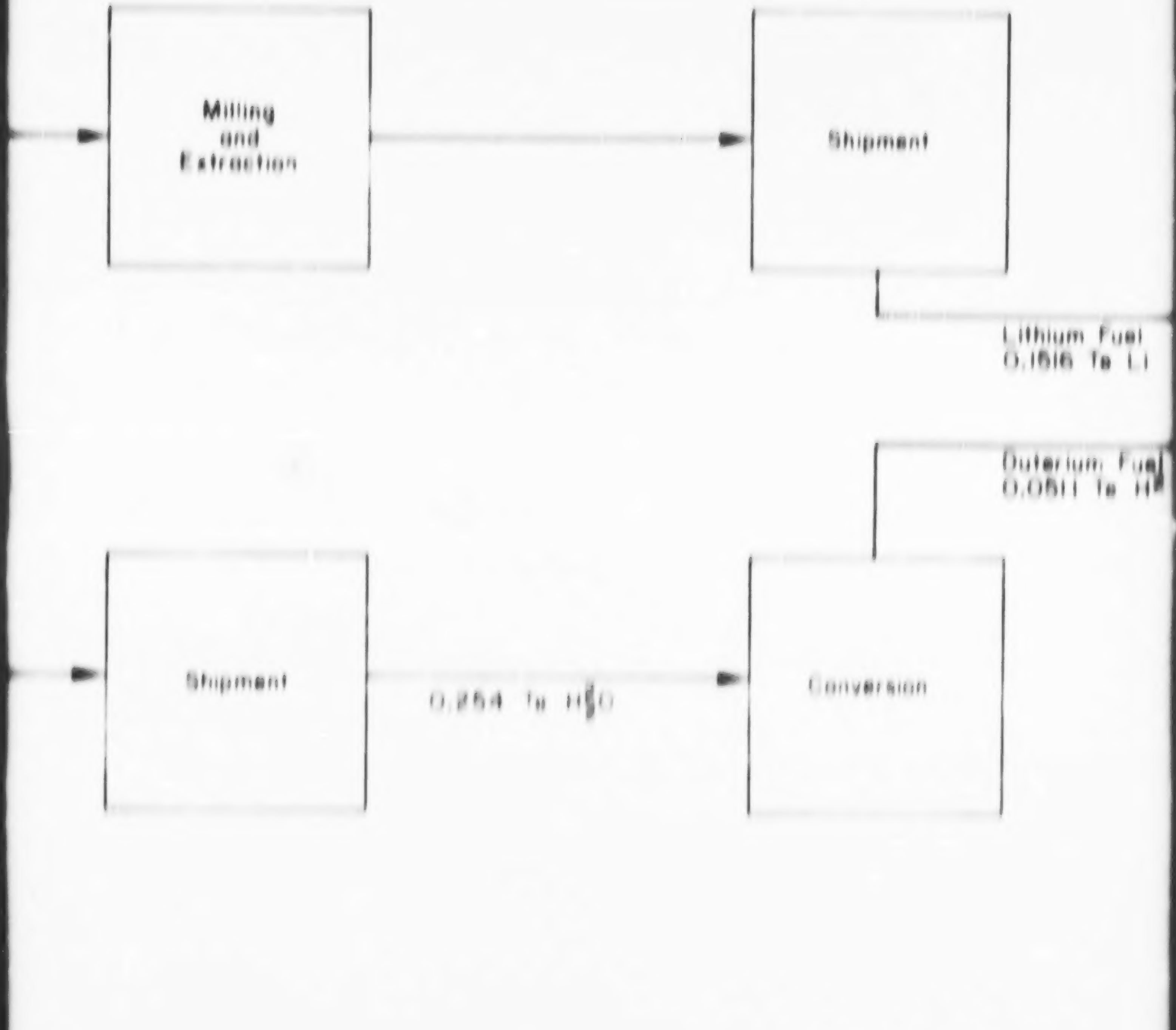
Fusion R
Material

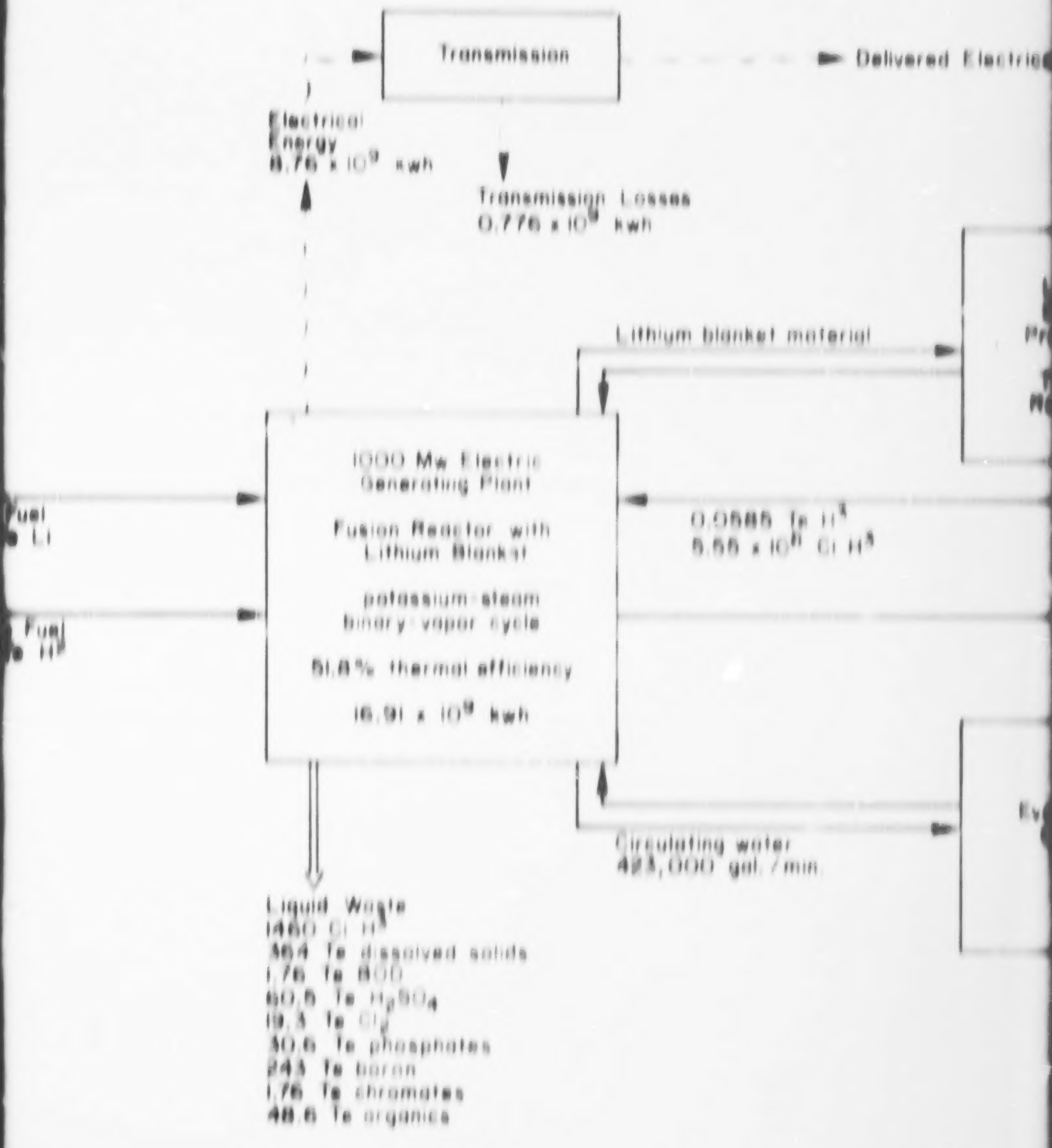


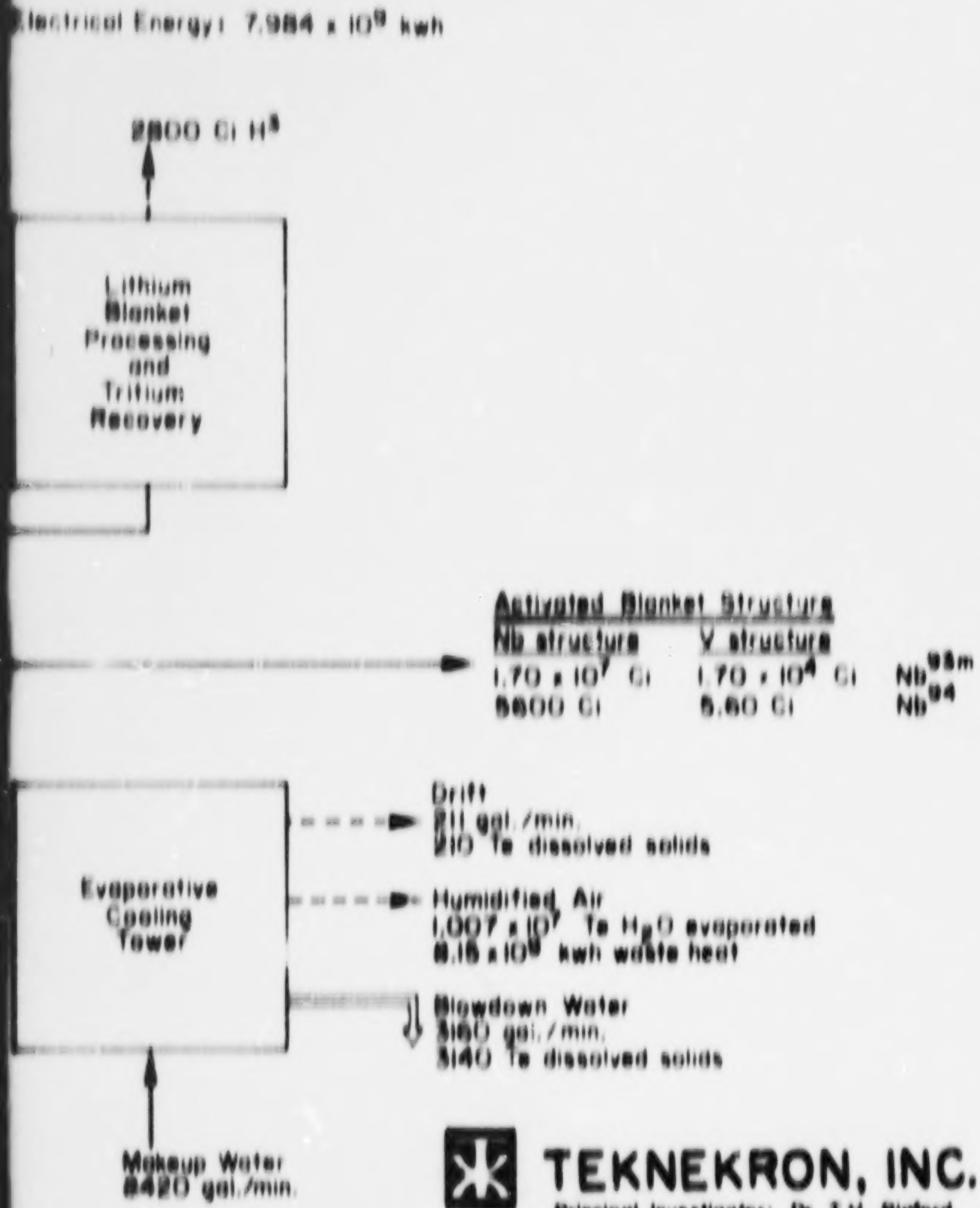
Open-Pit Mining
18.95 Te Pegmatite Ore containing 1.895 Te $LiAlSi_2O_6$
Overburden
H_2S Leakage
Isotope Separation
H_2S - H_2O Dual Temperature
Makeup Water: 9050 Te H_2O
H^2/H = 0.00014
H_2^2O Product
0.254 Te
H^2/H = 0.99+
Depleted Water
9050 Te H_2O
H^2/H = 0.00015

Figure 12.1

on Reactor Nuclear Plant 1000 Mwe
erial And Environmental Release Flowsheet


Milling and Extraction
Shipment
Lithium Fuel
0.1516 Te Li
Duterium Fuel
0.0511 Te H²
Shipment
0.254 Te H²O
Conversion


Transmission
Delivered Electric
Electrical Energy 8.76 x 10^9 kwh
Transmission Losses 0.776 x 10^9 kwh
Lithium blanket material
1000 Mw Electric Generating Plant
Fusion Reactor with Lithium Blanket
potassium-steam binary-vapor cycle
51.8% thermal efficiency
16.91 x 10^9 kwh
Fuel
Li
Fuel
H³
0.0585 Te H³
5.55 x 10^8 Ci H³
Circulating water 423,000 gal./min.
Liquid Waste
1460 Ci H³
364 Te dissolved solids
1.76 Te BOD
60.5 Te H₂SO₄
19.3 Te Cl₂
30.6 Te phosphates
243 Te boron
1.76 Te chromates
48.6 Te organics


Electrical Energy: 7.984 x 10^9 kwh
2800 Ci H^3
Lithium Blanket Processing and Tritium Recovery
Activated Blanket Structure
Nb structure
V structure
1.70 x 10^7 Ci
1.70 x 10^4 Ci
Nb^93m
5600 Ci
5.60 Ci
Nb^94
Drift
211 gal./min.
210 Te dissolved solids
Evaporative Cooling Tower
Humidified Air
1.007 x 10^7 Te H2O evaporated
8.15 x 10^9 kwh waste heat
Blowdown Water
3160 gal./min.
3140 Te dissolved solids
Makeup Water
8420 gal./min.

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turbine and is condensed by boiling water. The high-pressure steam expands through a conventional turbine. The calculated overall thermal efficiency of this dual cycle is 51.8%.

The steam condenser is cooled with water from the model evaporative cooling system, scaled to the heat rejection load for this cycle.

12.3 Fuel Materials

The quantities of deuterium and lithium consumed per year are calculated from the reaction rates quoted above. The deuterium fuel can be obtained from electrolytic decomposition of heavy water with an isotopic composition of over 99% H^2. The heavy water shipped to the power plant is obtained from a deuterium isotope-separation plant, which is assumed to operate on the dual-temperature process involving the isotopic exchange reaction between gaseous hydrogen sulfide and liquid water(8). The water fed to the isotope-separation plant is assumed to contain the natural isotopic abundance of 0.014 percent deuterium in hydrogen. A typical recovery(8) of 10% of the deuterium in the feed is assumed.

It is assumed that the blanket is designed so that the ratio of lithium isotopes in the blanket is the same as for natural lithium (7.52% Li^6) and that the reaction rates are such that the relative concentrations of Li^6 and Li^7 remain the same as in natural lithium. Otherwise lithium isotopic separation and/or withdrawal of depleted lithium from the blanket may be required, resulting in a larger net requirement for natural lithium. With these assumptions, the make-up lithium is calculated as the molar equivalent to the tritium production rate.

Lithium ore requirements are calculated on the basis of mining pegmatite ore with an assumed concentration of 10 percent spodumene ($LiAlSi_2O_6$)(4). The pegmatite ore containing spodumene is typically mined from 20-foot benches in a large open pit. The spodumene is recovered by crushing, screening, milling, and flotation. Extraction of lithium from spodumene involves either acid treatment or alkali treatment. Acid treatment involves calcining followed by sulfuric acid addition. The lithium sulfate is leached, neutralized with limestone, and filtered. It is then brought into water solution, precipated with soda ash, converted to the chloride by reacting with hydrochloric acid, and electrolyzed to metallic lithium.

Alkali extraction involves calcination of spodumene with limestone and hydrolyzing the calcined product with steam to produce lithium hydroxide. This is converted to the chloride and electrolyzed to metallic lithium.

Techniques of lithium isotope separation are described in Reference (3).

12.4 Tritium Losses

Steiner and Fraas(1) estimate a total tritium inventory of 6 kg. in their conceptual design of a 1000 Mw(t) fusion power plant, including 0.4 kg. of tritium in the lithium and potassium systems. They estimate that leakage of gaseous tritium from the lithium and potassium systems can be kept as low as 10^{-6} of the contained tritium per day, corresponding to a leakage fraction of 7×10^{-8}/day based on the total tritium inventory. The estimated leakage of tritium from the potassium system into the steam cycle, and ultimately into the plant cooling water, is 3 curies per day, which corresponds to a leakage fraction of 5×10^{-8}/day of the total tritium inventory.

Scaling these estimates to the present 1000 Mw(e) plant design, the total tritium inventory is 11.6 kg, or 1.1×10^{8} curies. The tritium leakage to the environment is 2800 curies per year of gaseous tritium and 2110 curies per year of tritium in liquid wastes.

These tritium releases are lower than the corresponding leakage fractions of tritium in water reactors. The total curie inventory of fission-product tritium in a water reactor is about 20,000 curies (cf. Section 8.7). The quoted leakage rate of about 100 curies per year for a boiling water reactor corresponds to a daily leakage fraction of 10^{-5}/day. The high operational temperatures contemplated for lithium blanket systems in fusion power plants and the finite permeability of structural materials to hydrogen at high temperature may make tritium containment difficult. For example, Fraas suggests tungsten coatings on some structural components to control tritium loss.

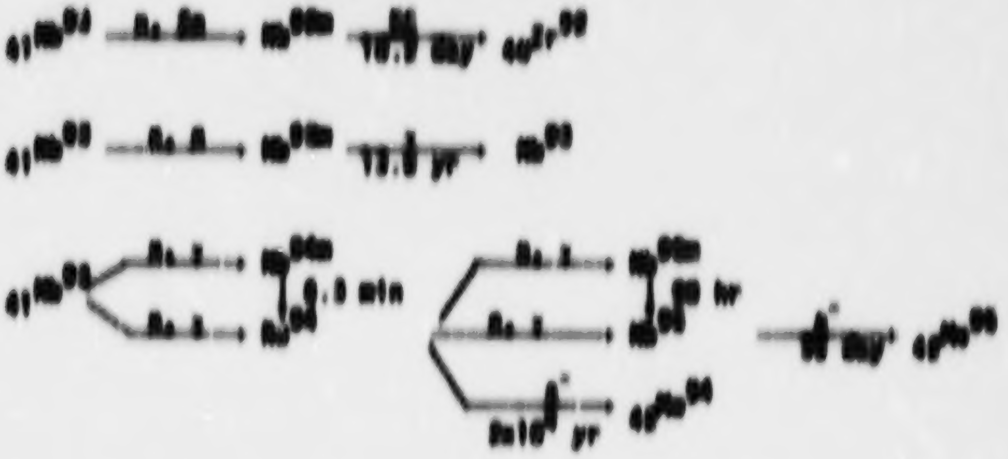
12.5 Activated Structural Material

Steiner and Fraas[1] have calculated the radioactive inventories in the structural system of their conceptual fusion reactor. Both niobium and, alternatively, vanadium blanket structures are considered. The principal neutron activation chains are shown in Table 12.1. The calculated radioactive inventories and the production rate of long-lived species are listed in Table 12.2.

Table [illegible].1

Neutron Reactions for Structural Activation in a Fusion Reactor[1]

Niobium Activation



Vanadium Activation

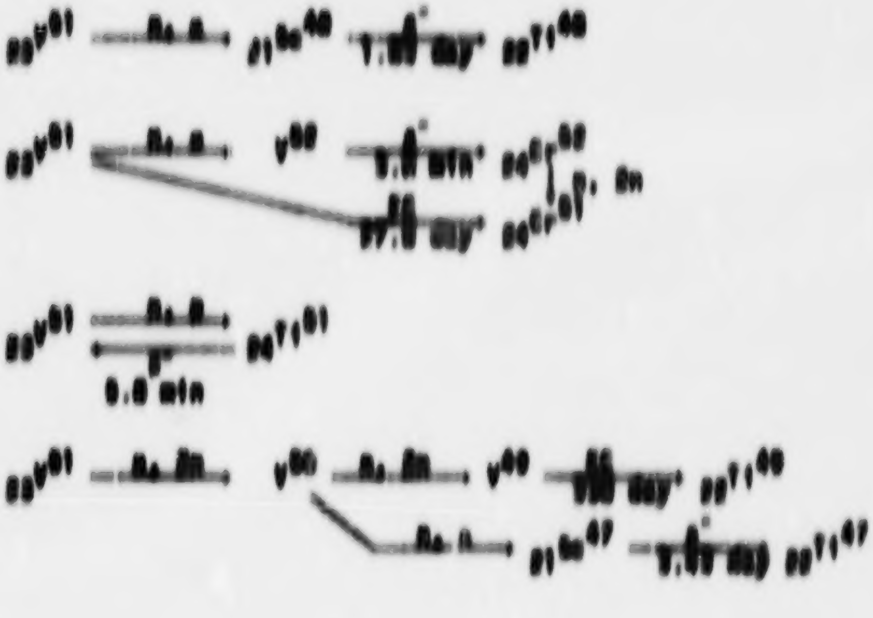


Table 12.2

Radioactivity in Fusion Reactor Blanket Structure

	curies per thermal kilowatt[1]	curies in 1000 Mw(e) fusion plant
Niobium Blanket Structure		
Nb^{95}	158	3.99×10^8
total niobium structure	714	1.86×10^9
Vanadium Blanket Structure		
Sc^{48}	4.20	0.11×10^8
total vanadium structure	66.1	1.66×10^8

nuclide	half life	rate of generation of long-lived radionuclides: curies per year per Mw(t)	curies per year in 1000 Mw(e) power plant
Niobium Blanket Structure			
Nb^{93m}	13.6 yr	6,600[1]	1.70×10^7
Nb^{94}	2.0×10^4 yr	2.0[1]	5,000
Vanadium Blanket Structure (assume 1000 ppm Nb)			
Nb^{93m}	13.6 yr	6.6	17,000
Nb^{94}	2.0×10^4 yr	0.0020	5.0

The actual rate of replacement of blanket structure is not yet specified. However, the blanket structure is expected to have a finite useful lifetime in the fusion power plant because of radiation damage. If the rate of blanket-structure replacement is less than the mean life of the long-lived species, the average rate at which these radionuclides are withdrawn from the reactor and sent to processing or disposal is equal to their production rate in the reactor. It is on this basis that the average yearly withdrawal rates of long-lived activated species in the blanket are calculated, and the results of these calculations are shown in the flow diagram.

REFERENCES

1. Steiner, D. and A. P. Fraas, "Preliminary Observations on the Radiological Implications of Fusion Power," Nuclear Safety 13-5, 353 (September, October, 1972).

2. Steiner, D., "A Review of ORNL Fusion Feasibility Studies," 5th Intersociety Energy Conversion Engineering Conference, Energy 70, Las Vegas, Nevada (September, 1970).

3. Benedict, M. and T. H. Pigford, "Nuclear Chemical Engineering," McGraw Hill (1957).

4. "Mineral Facts and Problems," Bulletin 630, 1965 ed., U. S. Bureau of Mines.

13. ELECTRICAL POWER TRANSMISSION

Two of the many environmental considerations associated with the transmission of electrical power are transmission losses and land required for transmission systems. According to the 1971 annual report of the Federal Power Commission[(1)], the 1971 production of electrical energy in the United States was 1.53 x 10^{12} kwh, and the 1971 sale of electrical power was 1.396 x 10^{12} kwh. This corresponds to an average of 8.86% of the generated power lost or consumed in delivery, resulting in the average yearly loss of 0.776 x 10^{9} kwh for a 1000 Mw(e) power plant (100% load factor) as shown on the flowsheets.

The Federal Power Commission reported that in 1968 there were over 300,000 miles of transmission lines, of 69 kilovolts or greater, in the United States[(2)]. The right of way occupied by this transmission system was estimated at 4 million acres. On an industry-wide basis, the average land requirement was 13.3 acres per mile of right of way. The total generating capacity in 1968 was 290,000 Mw(e)[(2)], which corresponds to an average transmission line distance of 1034 miles per 1000 Mw(e) of generating capability. The above data then led to the estimate of 14,700 acres of land for transmission associated with each 1000 Mw(e) power plant.

Other environmental effects associated with electrical transmission include visual impact, effects resulting from line and tower construction, and ozone production by corona discharge.[(3)]

REFERENCES

1. United States Federal Power Commission, "Annual Report - 1971," 11-18.

2. "Environmental Effects of Producing Electric Power," Hearings Before the Joint Committee on Atomic Energy, United States Congress (1971).

3. United States Department of the Interior, Bureau of Land Management, "Final Environmental Statement for the Jim Bridger Thermal-Electric Generation Project" (April, 1972).